BUREAU OF RECLAMATION

Technical Report No. ENV-2020-006

Twin Lakes 2017 Sedimentation Survey

Fryingpan Arkansas Project, Colorado
Great Plains Region

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Sedimentation and River Hydraulics Group
Denver, Colorado

February 2020

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Acknowledgements

Kent Collins, Robert Hilldale and Caroline Ubing from the Bureau of Reclamation's (Reclamation) Sedimentation and River Hydraulics Group at the Technical Service Center (TSC) conducted this survey in June of 2017. Vince Benoit completed the data processing and generated the surface presented in this report. Funding for this survey was provided by the Great Plains Regional Office.

Disclaimer

Cover: Twin Lakes Reservoir, Leadville, CO, (photo by: Caroline Ubing)

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14. SHORT ABSTRACT

The 2017 multibeam bathymetric survey of Twin Lakes Reservoir was combined with 2010 LiDAR data to produce a combined digital surface of the reservoir bottom. Analysis of this data indicates that at the top of active pool elevation (9,200 feet, Reclamation project vertical datum), the reservoir would have a surface area of 2,762 acres and a storage capacity of 140,749 acre-feet. Since the original filling in 1980 and modification in 1983, the reservoir is estimated to have lost storage capacity due to sedimentation. However, we cannot measure the change in storage area due to lack of repeat surveys using comparable survey techniques. We recommend a repeat survey in ten years to measure sediment accumulation rates, spatial distribution of deposited sediment and risk of sediment impacting reservoir operations.

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Twin Lakes Reservoir survey, sedimentation, capacity

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BUREAU OF RECLAMATION
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Sedimentation and River Hydraulics Group, 86-68240

Technical Report No. ENV-2020-006

Twin Lakes 2017 Sedimentation Survey

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Acronyms and Abbreviations

Approx.	approximately
ac-ft	acre-feet
cfs	cubic feet per second
DEM	digital elevation model
DOI	Department of the Interior
ft	foot (feet)
GIS	Geographic Information System
GPS	Global Positioning System
HUC	Hydrologic Unit Code
LiDAR	Light Detection and Ranging
m	meter
mi^2	square miles
NAD 1983	North American Datum, established 1983
NAVD 1988	North American Vertical Datum, established 1988
NGS	National Geodetic Survey
NGVD 1929	National Geodetic Vertical Datum, established 1929
NID	National Inventory of Dams
NRCS	Natural Resources Conservation Service
OPUS	Online Positioning User Service
Reclamation	Bureau of Reclamation
RPVD	Reclamation Project Vertical Datum
RSI	Reservoir Sedimentation Information
RTK	Real-Time Kinematic
SGMC	State Geologic Map Compilation
TSC	Technical Service Center
USGS	United States Geological Survey

Executive Summary

Twin Lakes Dam and Reservoir are on Lake Creek approximately 13 miles south of Leadville, Colorado.

A bathymetric survey of Twin Lakes Reservoir was conducted in 2017 with these primary objectives

1. Estimate reservoir sedimentation volume since the original reservoir filling began in 1980 and

2. Determine new reservoir surface area and storage capacity tables for the full elevation range of dam and reservoir operations.

The bathymetric survey was conducted from a boat using a multibeam depth sounder that was interfaced with real-time kinematic (RTK) global positioning system (GPS) instruments (for horizontal positioning) to map the reservoir bottom. The 2017 multibeam bathymetric survey of Twin Lakes Reservoir was combined with 2010 LiDAR data to produce a combined digital surface of the reservoir bottom.

This survey was conducted between June 19, 2017 and June 22, 2017 when the reservoir water surface elevation ranged between 9,195 and 9,197 feet (Reclamation project vertical datum, RPVD), three to five feet below the top of normal operations pool elevation of 9,200 feet. The above-water topographic data were measured in 2010.

Analysis of the combined data sets indicates the following results:

- At the spillway crest elevation (9,200 feet, RPVD), which is 3 to 5 feet above the water surface elevation at the time of survey, the reservoir surface area is 2,762 acres with a storage capacity of 140,749 acre-feet.

- At the top of the surcharge pool elevation (9,202.3 feet, RPVD), which is 5 to 7 feet above the water surface elevation at the time of survey, the reservoir surface area is 2,857 acres with a storage capacity of 147,220 acre-feet.

- Based on the 1964 data, the reservoir would have a surface area of 2,805 acres and a storage capacity of 140,930 acre-feet at the top of active conservation pool elevation (9,200 feet, RPVD).

- The original filling of the reservoir occurred in 1980; a drawdown for modifications were required in 1983. While sedimentation has surely occurred in the 37 years between initial reservoir filling and the 2017 survey, the loss in storage is smaller than the error between the two surveys and cannot be determined. A repeat survey is recommended in 2027 to quantify the basin's annual sediment yield and determine spatial deposition patterns.

- Additionally, no change in reservoir storage could be detected between the original and 2017 survey, the reduction in the dead storage pool volume is also unknown. The depth of sediment within the dead storage pool can determine the risk of sediment impacting the outlet structure, which can impact reservoir operations. A better understanding of reservoir sedimentation in Twin Lakes Reservoir will inform the reservoir's expected useful life.

A summary description of the dam, reservoir, and survey results is presented in Table ES-1.

Table ES-1. Reservoir Survey Summary Information

Reservoir Information

Reservoir Name	Twin Lakes Reservoir	Region	Great Plains
Owner	Bureau of Reclamation	Area Office	Fryingpan-Arkansas
Stream	Lake Creek	Vertical Datum	RPVD (approx. NGVD29)
County	Lake County	Top of Dam (ft)	9,210
State	Colorado	Spillway Crest (ft)	9,200
Lat (deg min sec)	39° 4′ 44″	Power Penstock Elevation (ft)	N/A
Long (deg min sec)	106° 18′ 10″	Low Level outlet (ft)	9,157.5
HUC4	1102	Total Drainage Area (mi^2)	105
HUC8	11020001	Date storage began	1980
NID ID	CO02045	Date for normal operations	1983
Dam Purpose	municipal, irrigation, recreation, afterbay for Mt. Elbert Pumped-Storage Powerplant		

HUC = Hydrologic Unit Code; NID = National Inventory of Dams

Original Design

Storage Allocation	Elevation (feet)	Surface area (acres)	Capacity (acre-feet)	Gross Capacity (acre-feet)
SURCHARGE	9,202.3	2,893	6,500	147,500
CONSERVATION	9,200	2,805	68,000	140,930
INACTIVE	9,168.7	1,698	18,000	73,000
DEAD	9,157.5	1,529	55,000	55,000

Survey Summary

Survey Date	**Type of Survey**	**No. of Range lines or Contour Intervals**	**Contributing Sediment Drainage Area (mi^2)**	**Period Sediment-ation Volume (acre-feet)**	**Cumulative Sediment-ation (acre-feet)**	**Lowest Reservoir Elevation (feet)**	**Remaining Portion of Dead Storage (%)**
1964	Unknown	5-ft	105			9,101	100%
2017	Multibeam	1-ft	105	280	280	9,097	100%

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1. Introduction

Twin Lakes Dam and Reservoir are on the Lake Creek, tributary to the Arkansas River, approximately 13 miles south of Leadville, Colorado (Figure 1). Twin Lakes were a natural geologic feature, formed by glacial deposits. Twin Lakes Dam was built in 1980 on the lower moraine and modified in 1983. The dam and reservoir are operated by Eastern Colorado Area Office as part of the Fryingpan-Arkansas Project that is designed to divert water from the Western Slope to water-short areas on the eastern slope providing water for irrigation and municipal use. Twin Lakes Reservoir also serves as an afterbay for Mt. Elbert Pumped-Storage Powerplant (Reclamation, 2005).

All rivers transport sediment particles (e.g., clay, silt, sand, gravel, and/or cobble) and reservoirs tend to trap sediment, diminishing the reservoir storage capacity over time. Reservoir sedimentation affects all elevations of the reservoir, even above and upstream of the full pool elevations. Cobble, gravel, and sand particles tend to deposit first forming deltas at the upstream ends of the reservoir while silt and clay particles tend to deposit along the reservoir bottom between the delta and dam.

Periodic reservoir surveys measure the changing reservoir surface area and storage capacity and provide information for forecasting when important dam and reservoir facilities will be impacted by sedimentation.

As part of ongoing operations and sediment monitoring activities, Great Plains Regional Office requested the Technical Service Center's (TSC) Sedimentation and River Hydraulics Group (86-68240) to conduct a bathymetric survey of the underwater portions of the reservoir that were accessible by boat. A complete bathymetric survey was conducted from 6/19/2017 to 6/22/2017 with these primary objectives:

1. Estimate reservoir sedimentation volume since the original construction in 1980 and

2. Determine new reservoir surface area and storage capacity tables for the full elevation range of dam and reservoir operations.

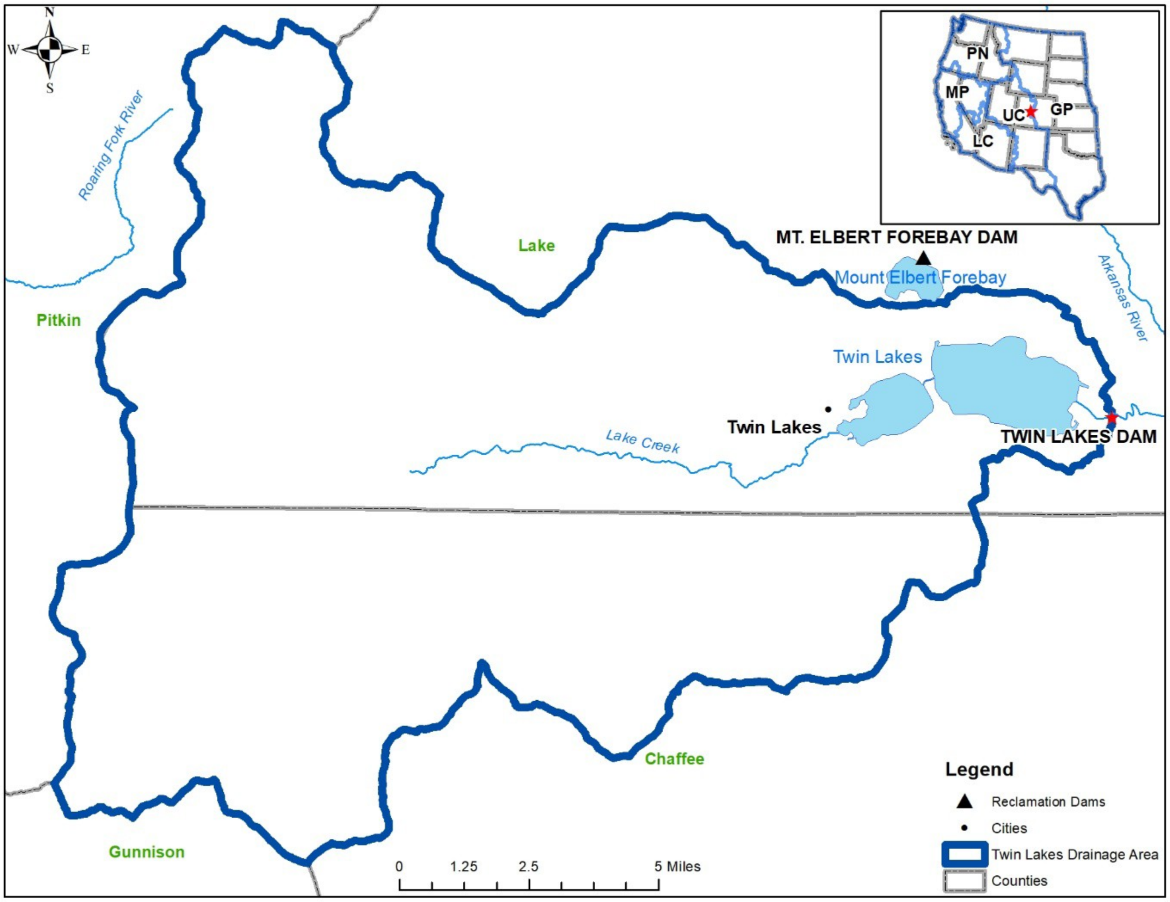


Figure 1. Location map of Twin Lakes Dam and Reservoir, approximately 13 miles south of Leadville, CO. Contributing drainage area is outlined in blue.

2. Watershed Description

The watershed upstream from Twin Lakes Dam has a total contributing drainage area of 105 square miles (mi^2). There are no upstream lakes or reservoirs that could trap sediment (as of 2019), the net sediment-contributing drainage area to Twin Lakes is also 105 mi^2 (Figure 2). The contributing watershed is in the Sawatch Mountain Range and largely unaltered. It extends west to the continental divide at the headwaters. Lake Creek is a headwater stream with cobble- and gravel-bed and thick, well-established vegetation.

Precipitation, land classification, and average basin slope can inform sediment supply from the contributing basin. Mean annual precipitation is 27 inches (85% of the mean annual precipitation of the United States). The three largest land classifications are grassland/herbaceous (35%), forest (28%), and barren (26%). Only 2.4% of the basin has been classified impervious (U.S. Geological Survey, 2011). Basin elevation ranges from 9,160 ft to 14,400 ft with an average elevation of 11,500 ft. The mean basin slope computed from 10 m DEM is 44% (U.S. Geological Survey, 2019). Lower than average mean annual precipitation and vegetation in over

50% of the basin suggest low sediment runoff from the watershed. However, the steep hillslopes will encourage overland erosion, increasing the potential sediment supply to Twin Lakes Reservoir.

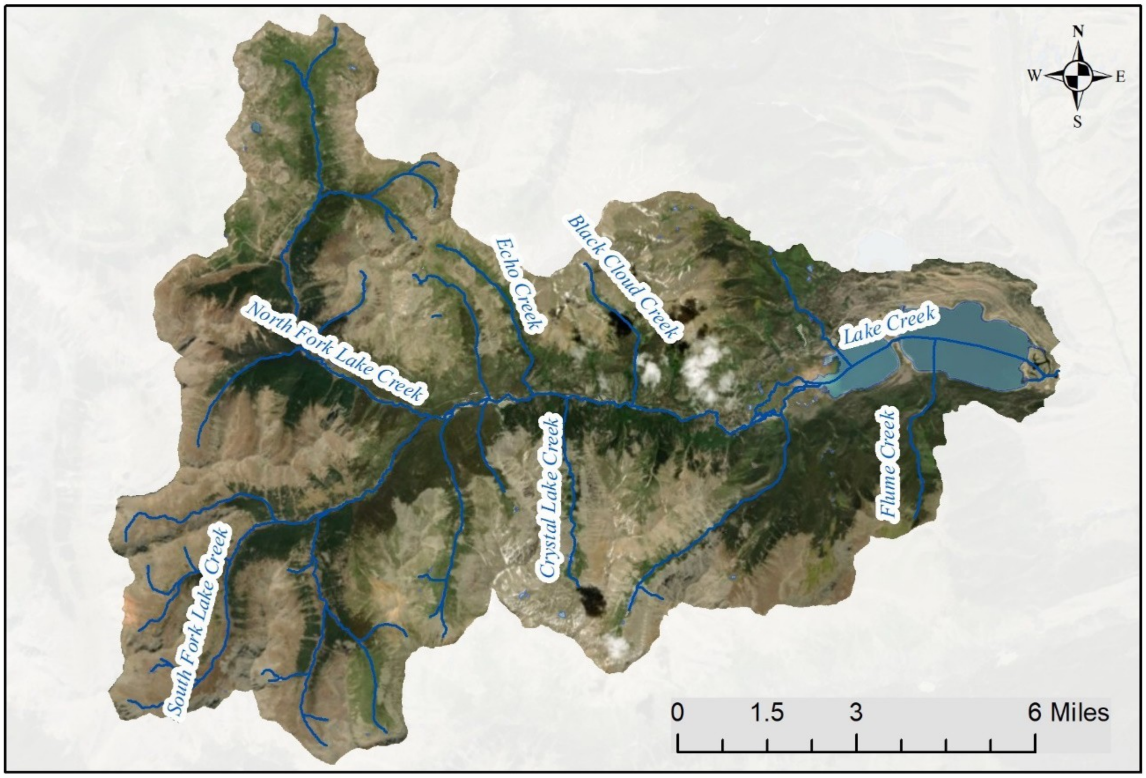


Figure 2. The watershed above Twin Lakes Dam has a total drainage area and a sediment-contributing drainage area of 105 mi².

2.1. Geology and Vegetation

The surrounding geology is highly impacted by glaciation, moraine recession and fluvial erosion (Figure 3). The river valley was formed by two periods of glaciation occurring during the Pleistocene Era, which extended beyond the narrow valley, building great terminal moraines (Capps & Leffingwell, 1904). Moraine recession occurred along Lake Creek to create the original two lakes. A series of low morainic knolls join with the main moraine to create the Lower Lake. A second low recessional moraine arches across the valley, which separates the two lakes (Westgate, 1905). Lake Creek valley is largely comprised of quaternary alluvium and glacial deposits (McCalpin, Funk, & Mendel, 2012) consisting of granite (Westgate, 1905). While granite is relatively resistant to weathering (as opposed to limestone), porphyritic granite has a somewhat greater capacity for weathering. Signs of fluvial erosion are observed in high deposits of gravel, in some cases 1,000 feet above the river. Hanging valleys and truncated spurs suggest that Lake Creek has moved considerable sediment since the last glacial period. Considerable sediment deposition has created the meadow at the upstream end of Upper Twin Lake. Landslides and rock-weathering contribute to the sediment supply of the reach (Westgate, 1905).

The geologic evidence of large sediment loads produced in the Lake Creek basin spans millions of years. Large sediment loads appear to be episodic, associated with glacial recession or landslides. Despite the above history, it is possible that low sediment loads have been observed in the more recent past (tens of years) since the reservoir was constructed.

Soils are primarily loam and gravelly sandy loam (Figure 4). Loams are a combination of gravels, sands, silts and clays. These soil textures tend to have a high sand content and low clay content, meaning they have good infiltration properties and are easily eroded (Soil Survey Staff, 2017).

The specific type of grasses or herbaceous plants in this watershed are unknown but make up 35% of the watershed. Vegetation types within the forested portion of the watershed (28%) primarily consist of thick forest containing pine trees and aspen groves. Land use activities within the watershed primarily consist of forest, with one road running longitudinally through the basin. Sediment yields are not predicted to be impacted by humans, and therefore consistent with natural loads.

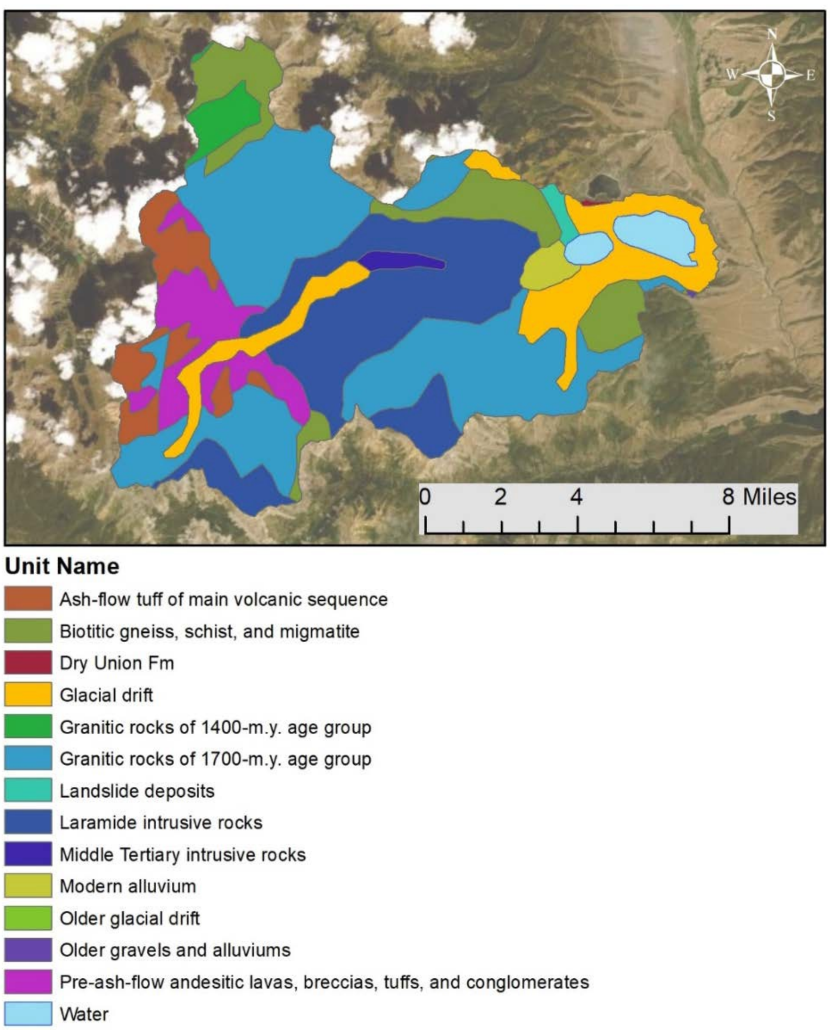


Figure 3. Geologic units within the Twin Lakes watershed.

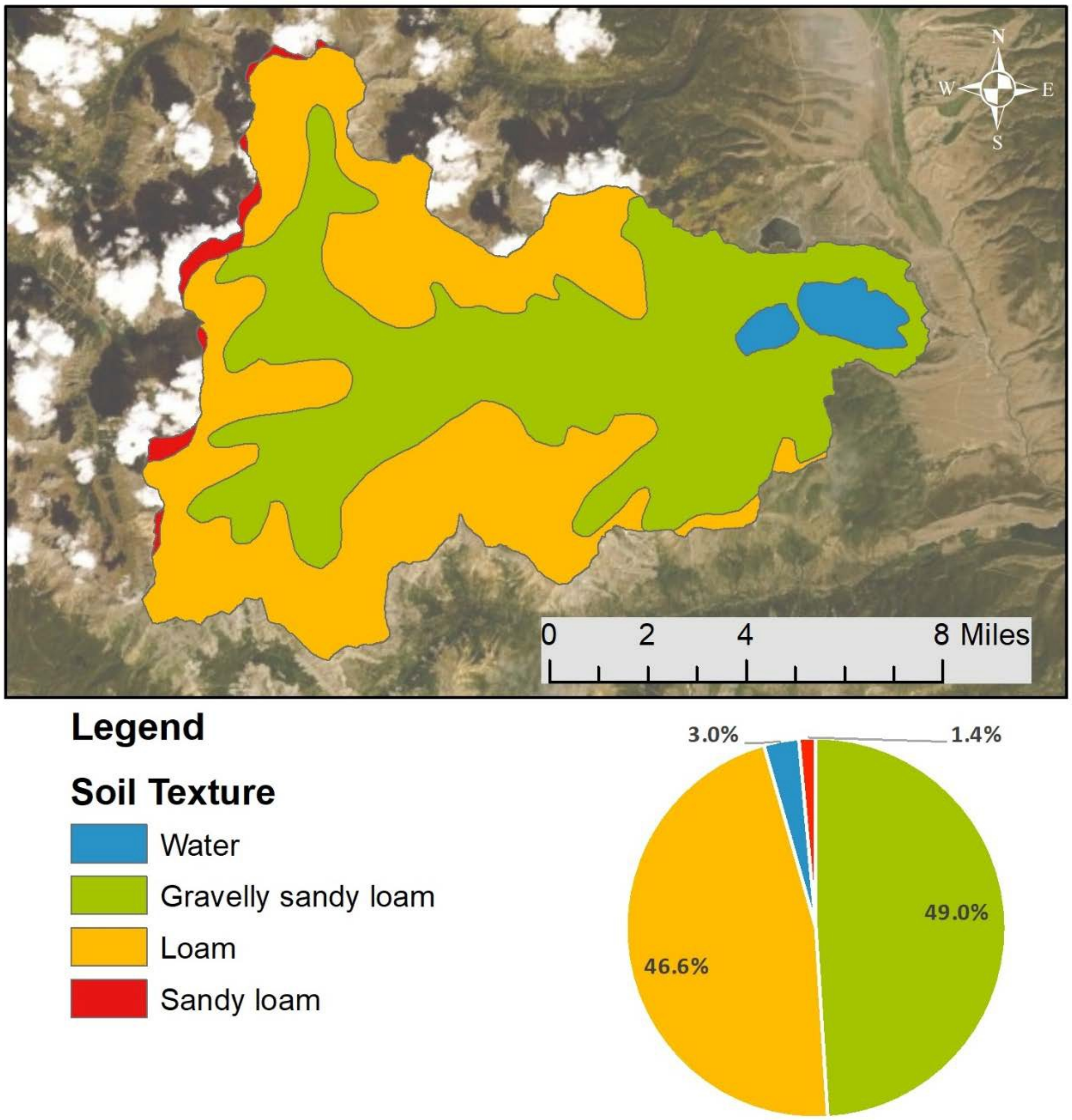


Figure 4. Soil texture within the Twin Lakes watershed.

2.2. Climate and Runoff

Reservoir inflows are primarily from Lake Creek, a headwater stream fed by four tributaries: South Fork Lake Creek, North Fork Lake Creek, Echo Creek, and Black Cloud Creek. Flume Creek feeds directly into the Lower Lake. Two historic USGS stream gage records are available for the locations presented in Table 1. The gage below Twin Lakes Reservoir only contains eight peak streamflow values and represents 100% percent of the total contributing drainage area. The second gage contains both daily data and peak streamflow data. It represents 70% of the contributing drainage area into Twin Lakes Reservoir.

Based on USGS data presented in Table 1, the mean annual runoff to Twin Lakes Reservoir is 26 inches per year or 104,000 acre-feet per year. This runoff is primarily snowmelt driven, where stream flow peaks each year in May or June. On average, streamflow peaks around 1,800 cubic feet per second (cfs) (Figure 5). The highest recorded peak streamflow was 3,270 cfs in 1978. The mean annual stream flow to the reservoir is 143 cubic feet per second (cfs). The ratio of reservoir storage capacity to the mean annual runoff is 1.4. This means that, when full, the reservoir stores a water volume equivalent to 495 days of mean annual stream flow.

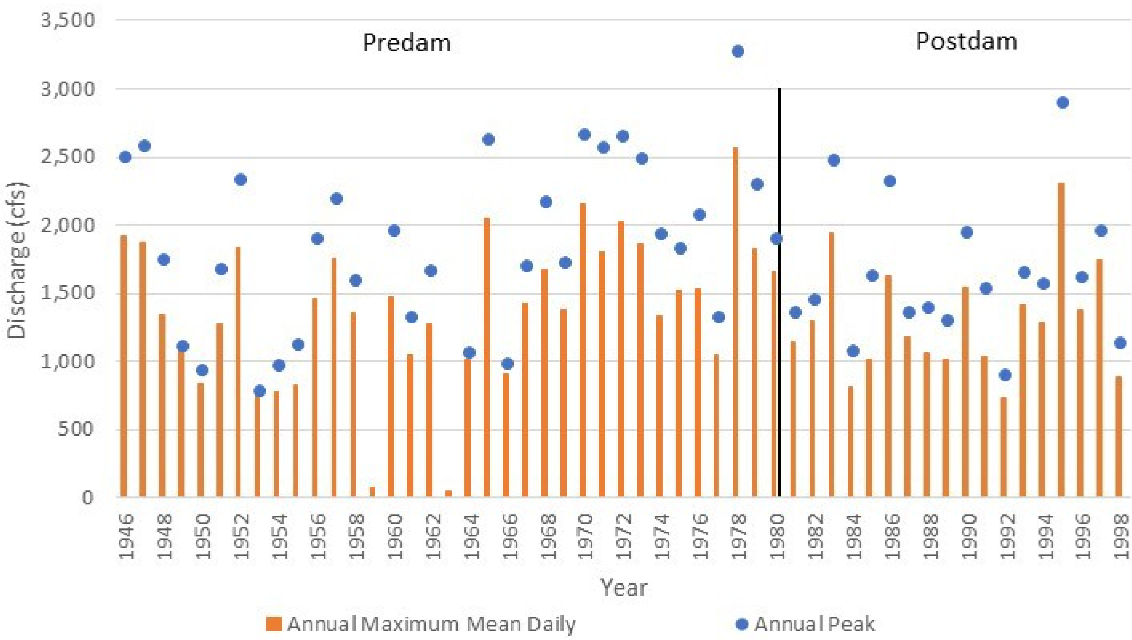


Figure 5. Maximum daily discharge for each year on Lake Creek above Twin Lakes Reservoir, representing 75% of the basin drainage area from 1946 to 1998.

Table 1. Reservoir Inflow Streams with USGS gages.

USGS Stream Gage		Drainage Area (mi^2)	Mean Annual Runoff (cfs)	Period of Record
Name	**Number**			
Lake Creek Below Twin Lakes Reservoir	07085500*	107		1946 – 1953
Lake Creek Above Twin Lakes Reservoir	0784500	75	143	1946 - 1998

* only peak discharge data are available at this gage.

2.3. Dam Operations and Reservoir Characteristics

Twin Lakes Dam is an earthen embankment dam. This dam was completed in 1980 and modified in 1983. The historic reservoir water surface elevations (RPVD) is presented in Figure 6. Annually, reservoir water surface typically fluctuates about 17 feet.

The dam has a height above the original stream bed of 55 feet and the reservoir had an original length of about 4.6 miles long at full pool with two contributing tributaries: Lake Creek and Flume Creek. The spillway is located near the left abutment and has a 1,400 cfs capacity with a crest elevation of 9,200 ft. It is an uncontrolled concrete morning-glory inlet structure with a 9-foot diameter conduit, feeding a concrete stilling basin below the dam. The reservoir is operated to avoid usage of the spillway, which was last employed in 1986.

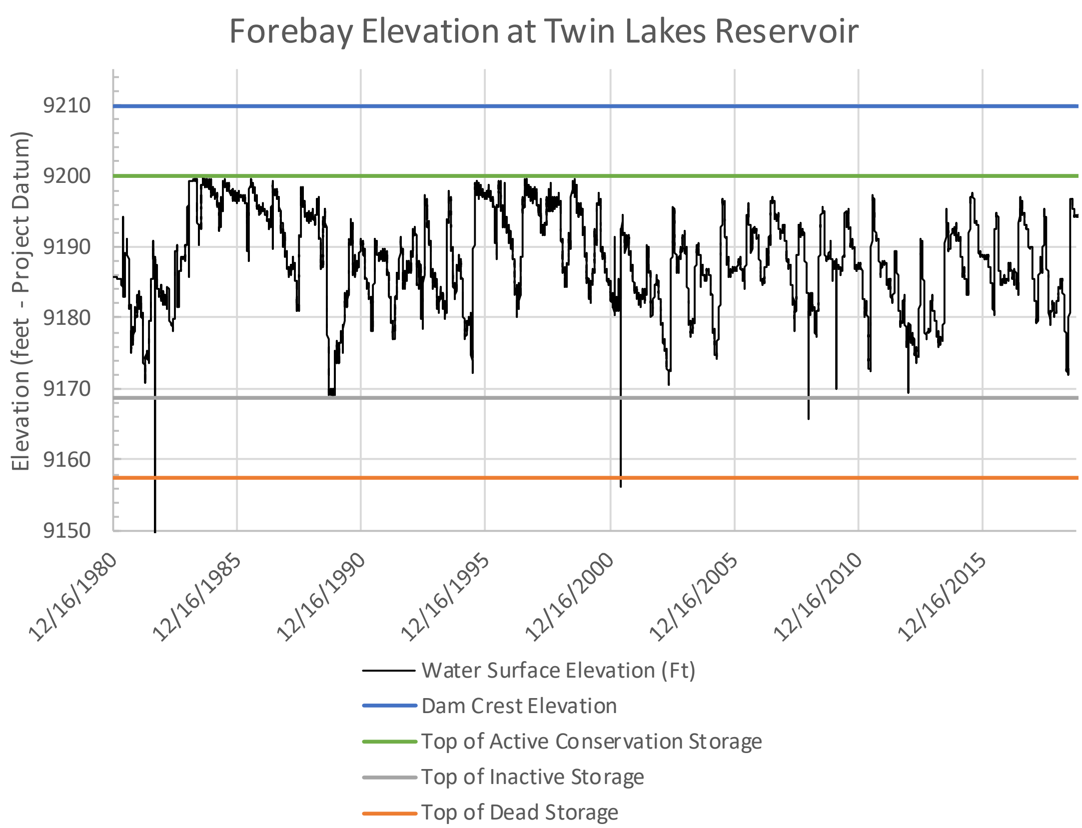


Figure 6. Historic Twin Lakes water surface elevations. Data web source: www.usbr.gov/gp/hydromet/. Horizontal lines represent the dam crest elevation, top of active storage pool, inactive storage elevation and dead storage pool elevation.

The reservoir is widest within the Lower Lake and narrowest in between the two lakes (Figure 1). A delta has formed near the upstream end and has progressed downstream approximately 0.7 miles. We would expect to see most sediment accumulation occurring within the delta in the Upper Lake. Due to the constriction between the two lakes, we would not expect to see a large volume of sediment depositing in the Lower Lake. Reservoir drawdown can help move sediment downstream, out of the delta. This practice has only occurred three times where daily average water surface elevation was recorded below 9,168.7 ft (the top of the inactive pool): 1982, 2001 and 2008. High reservoir levels can result in higher deposition rates. Higher reservoir levels were observed between 1984 and 1987 and again between 1995 and 2000. However, there is no record of past reservoir sediment management activities, nor are there repeat surveys to confirm or contradict sediment accumulation or evacuation during those time periods.

3. Previous Reservoir Survey(s)

Prior to dam closure and initial reservoir filling, this is the first survey conducted to measure surface area and corresponding storage capacities. Although the documentation summarizing the original survey methods has not been located for this analysis, range line survey would have been the most likely survey methods for this time period. No contour map has been found from this original survey. Area and capacity tables were produced in 5-foot increments.

4. Survey Control and Datum

For the 2017 survey, all bathymetry and GPS control measurements were collected in North American Datum 1983 (NAD 1983) State Plane (horizontal) coordinates, Colorado Central US survey feet and North American Vertical Datum 1988 (NAVD 1988, Geoid 12A, US survey feet elevations). During processing, all bathymetry and GPS measurements were converted to Reclamation Project Vertical Datum (RPVD) for Twin Lakes Dam, near National Geodetic Vertical Datum established in 1929 (NGVD 1929). The RPVD was determined to be approximately equivalent to NGVD 1929 and 5.62 survey feet lower than NAVD 1988, Geoid 12A).

The GPS base station receiver was set up over a temporary monument located near the boat ramp at Dexter Point Campground (Figure 7).

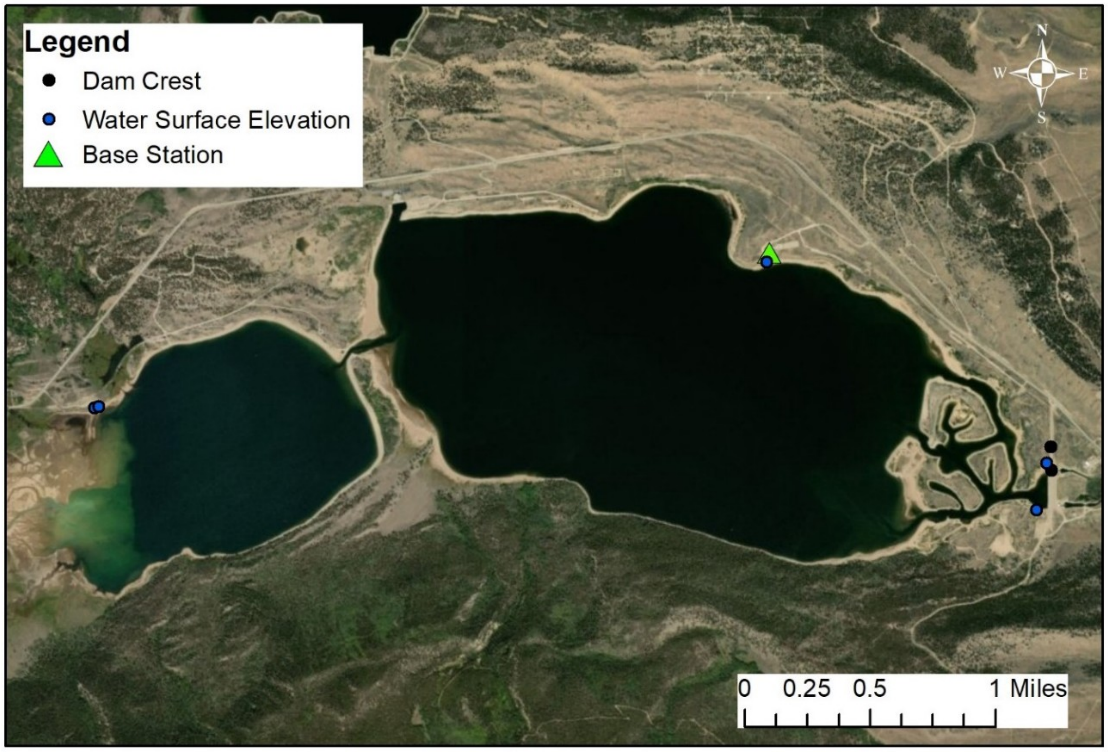


Figure 7. Location of GPS base station and survey points along Twin Lakes Reservoir.

State plane and elevation coordinates for the GPS base station were computed using the Online Positioning User Service (OPUS) developed by the National Geodetic Survey (NGS) (www.ngs.noaa.gov/OPUS/).

The RPVD at Twin Lakes Reservoir was determined from RTK GPS measurements on the dam crest and water surface elevations measured at the dam and boat launch

The difference between NGVD 1929 and NAVD 1988 at Twin Lakes Dam was computed using the US Army Corps of Engineers conversion program Corpscon v6.0.1. Corpscon uses NGS data and algorithms to convert between various horizontal projections and vertical datums (www.agc.army.mil/Missions/Corpscon.aspx). The Corpscon calculations confirmed that NGVD 1929 is 5.53 survey feet lower than NAVD88 at the base station location.

5. Methods Summary

A complete bathymetric survey was conducted during June 2017 from a boat using a multibeam depth sounder to continuously measure water depths. The horizontal position of the moving boat was continually tracked using RTK GPS. A map of the data points collected is presented in Figure 8.

Appendix A provides more details of the hydrographic survey methods. These bathymetric data were combined with LiDAR data collected by the USGS above water during September and October of 2010 to produce a digital surface of the reservoir bottom surface.

Appendix B provides more details regarding the above -water survey data. Surface areas at 1-foot contour intervals were computed using GIS software and the computer program ACAP (Reclamation, 1985) was used to produce the reservoir surface area and capacity tables at 0.01-foot increments.

Appendix C provides more details about the methods used to generate surface area and storage capacity tables.

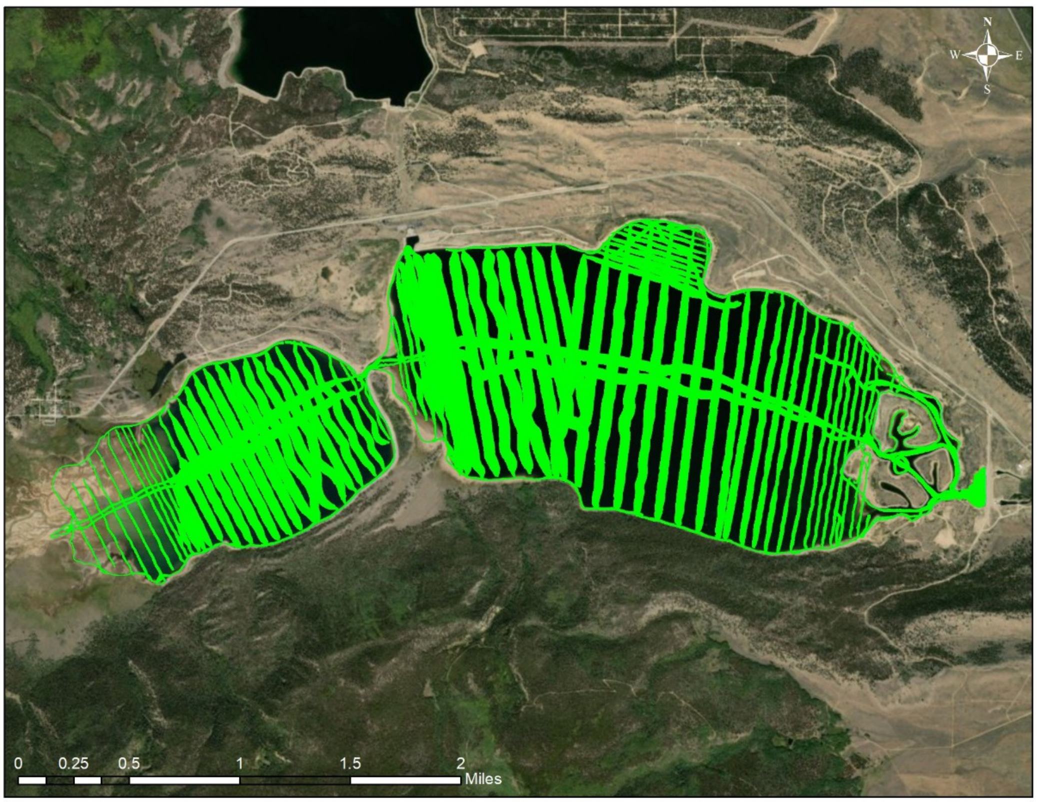


Figure 8. Map of bathymetric survey data coverage.

6. Reservoir Surface Area and Storage Capacity

Tables of reservoir surface area and storage capacity were produced for the full range of reservoir elevations (Twin Lakes Area and Capacity Tables 2017). The 2017 area and capacity data are presented in Figure 9 and Table 2, along with the original capacity curve from 1964. For the 2017 survey, area and capacity curves are based on the bathymetric (below-water) survey up to 9,190 feet elevation (RPVD), while curves above this elevation are based on 2010 aerial LiDAR (USGS, 2014). A comparison of these curves indicates no reduction in surface area or storage capacity between the 1964 and 2017 survey.

At the spillway elevation (9,200 feet, RPVD), which is 3 to 5 feet above the water surface elevation at the time of the survey, the reservoir surface area is 2,762 acres with a storage capacity of 140,749 acre-feet. At the top of surcharge pool elevation (9,202.3 feet, RPVD), the reservoir would have a surface area of 2,857 acres and a storage capacity of 147,220 acre-feet.

Table 2. Tabular surface area and capacity values by elevation

	Surface Area (acres)		Capacity (acre-ft)	
Elevation	**1964**	**2017**	**1964**	**2017**
9100	0	0	0	0
9110	426	402	1,726	1,581
9120	851	853	8,405	8,276
9130	1,100	1,108	18,243	18,234
9140	1,285	1,293	30,201	30,260
9150	1,443	1,453	43,882	44,017
9160	1,557	1,553	58,886	59,095
9170	1,723	1,728	75,206	75,424
9180	1,990	2,000	93,798	94,073
9190	2,329	2,289	115,200	115,408
9200	2,805	2,762	140,930	140,749
9202.3	2,893	2,857	147,500	147,220

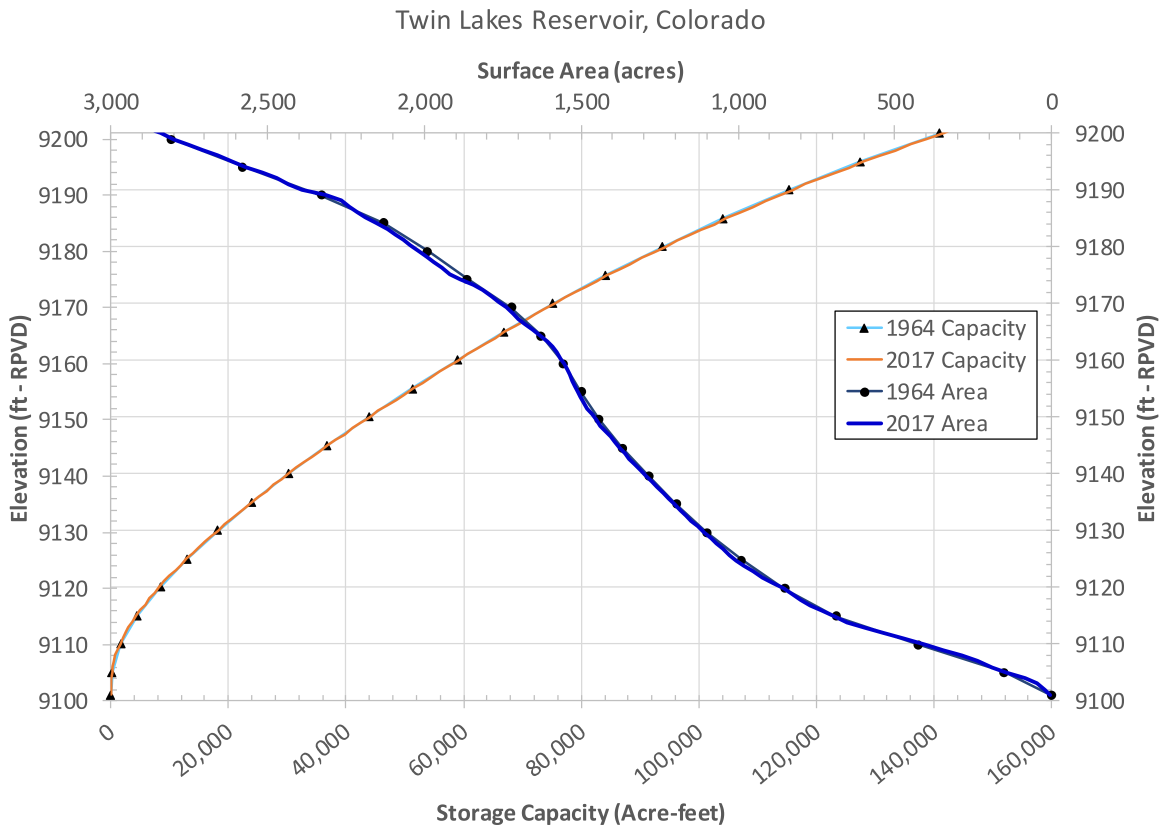


Figure 9. Plot of Twin Lakes Reservoir surface area and storage capacity versus elevation (RPVD).

7. Reservoir Sedimentation Volume Spatial Distribution

A longitudinal profile and representative cross sections of the 2017 reservoir bottom surface were developed in GIS along the alignments presented in Figure 10. Because there are no repeat surveys, we cannot say where sediment has deposited. We can make some assumptions based on theory and sedimentation trends in other reservoirs. Sedimentation is typically thickest in the river delta. The longitudinal profile shows a steep slope in this section, which could have been formed by delta deposits (Figure 11). Figure 12 through Figure 14 present representative cross sections. If sediment has deposited in these reaches, it is likely sediment deposited evenly across the width of the reservoir. Repeat surveys would likely confirm any assumptions on depositional patterns.

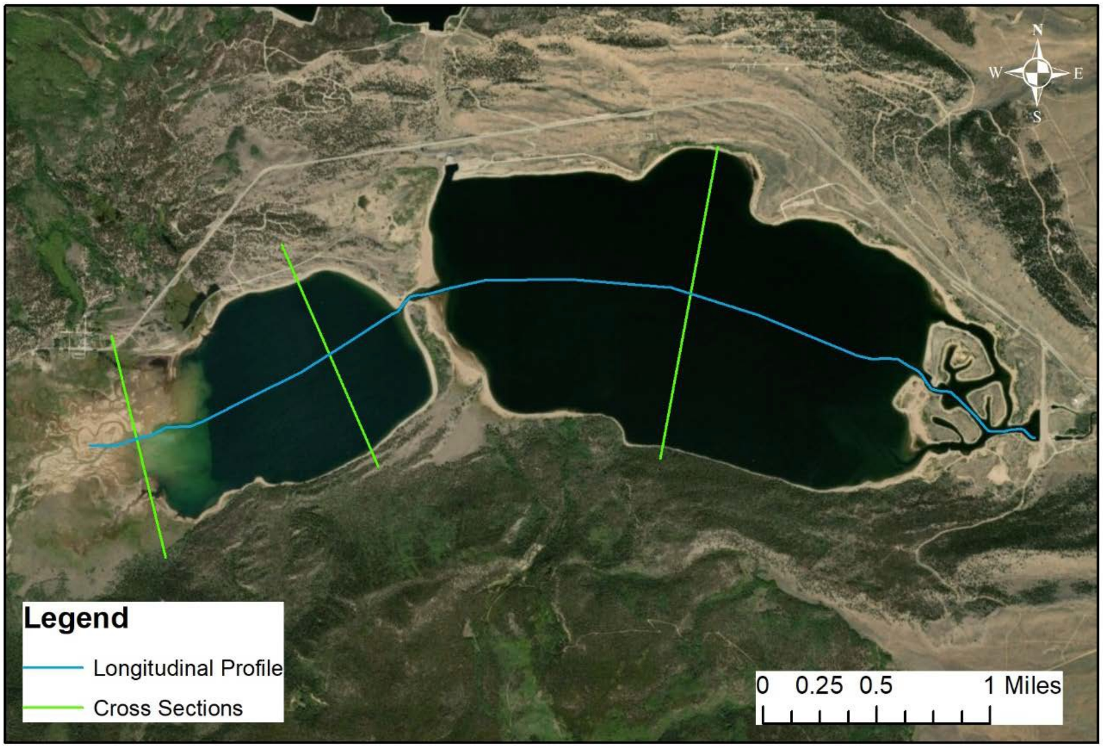


Figure 10. Reservoir surface elevation map and alignments of longitudinal profile and representative cross sections.

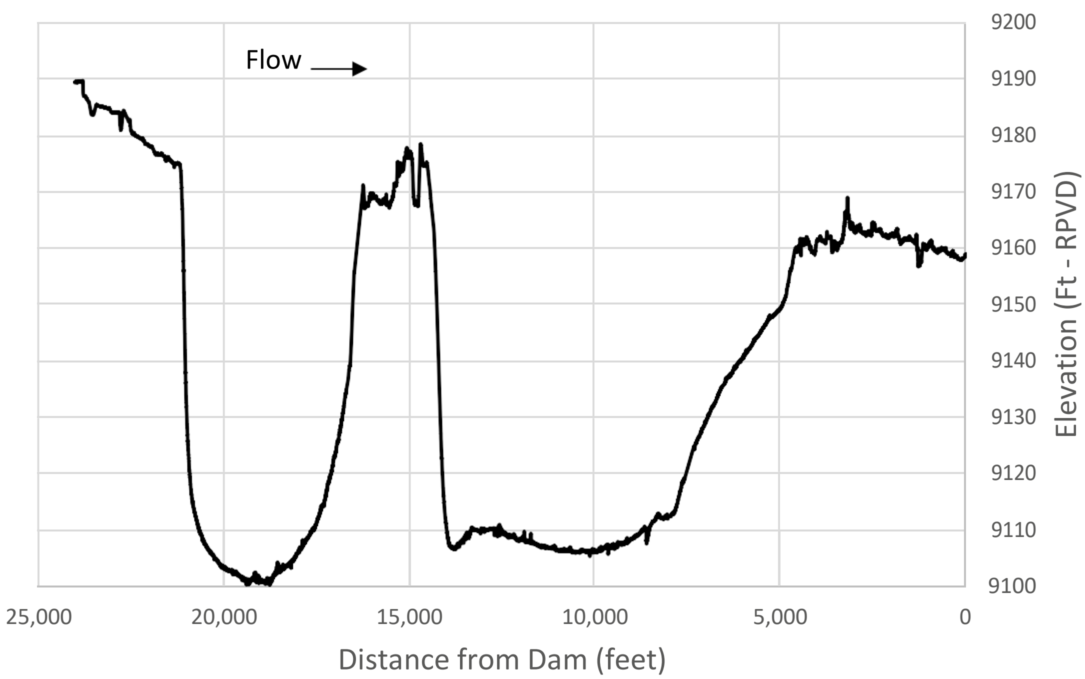


Figure 11. Longitudinal profile of Twin Lakes Reservoir bottom from the dam (x=0) to the river delta.

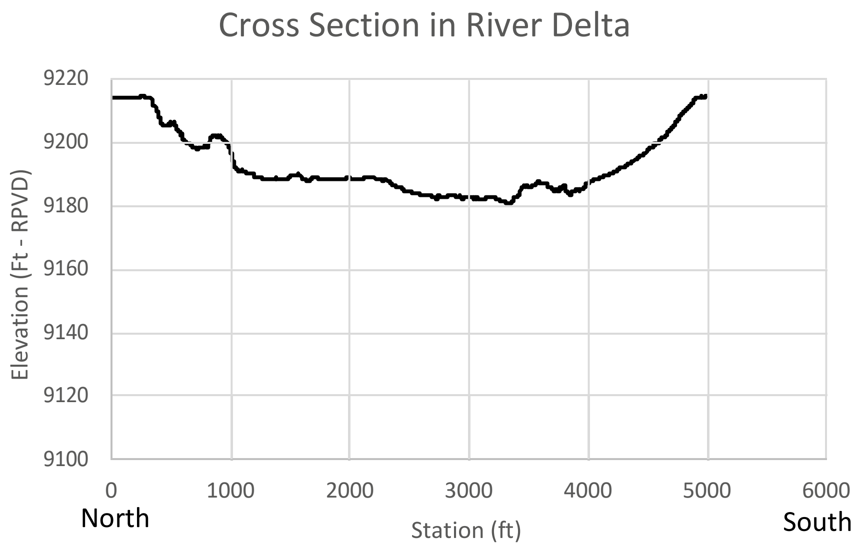


Figure 12. Representative cross section of the river delta in the Upper Lake, 4.3 miles upstream of Twin Lakes Dam. Based on the geometry, we can guess that sedimentation has likely formed evenly across the reservoir. A repeat survey using the same methodology would confirm this hypothesis.

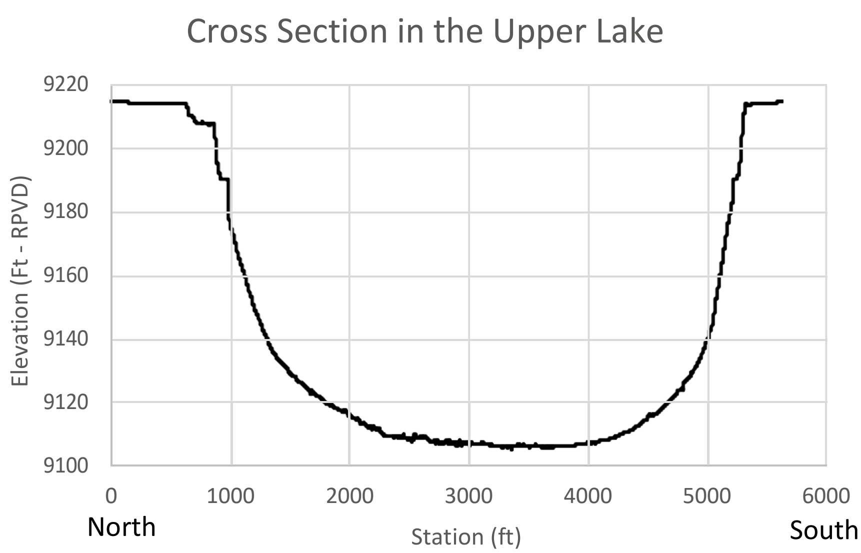


Figure 13. Representative cross section of the middle of the Upper Lake, 3.4 miles upstream from the Twin Lakes Dam.

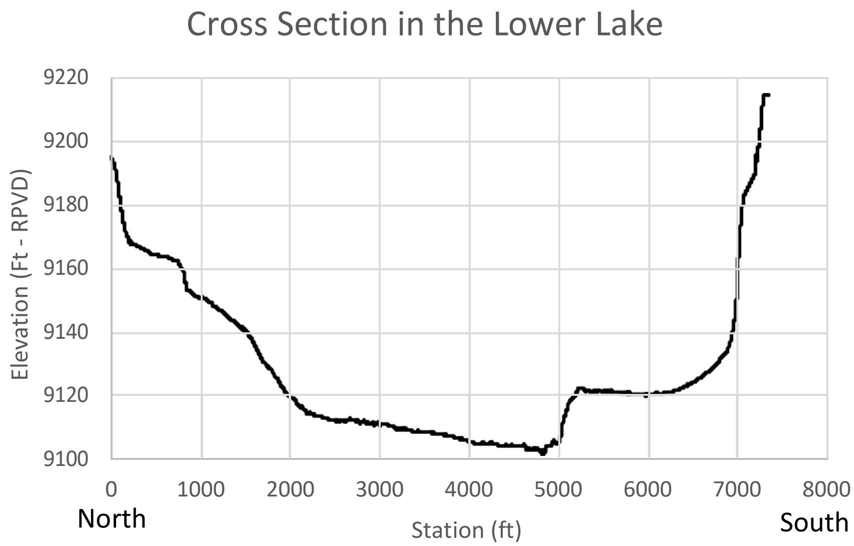


Figure 14. Representative cross section of the widest section of the Lower Lake, 1.7 miles upstream from the Twin Lakes Dam. The terrace formed on south bank does not appear to be a result of sedimentation, but rather historic glacial activity. However, we cannot confirm this hypothesis as there are no historic surveys.

8. Sedimentation Trends

There is no measurable change in reservoir capacity since the original 1964 survey. The 2017 survey reports an increase of 440 acre-ft of storage capacity. This discrepancy is due to differences in survey styles and accuracy rather than a physical increase in reservoir storage. On the contrary, it is likely the sediment has accumulated over time. The sedimentation rate into Twin Lakes Reservoir is unknown. Repeat surveys using the same survey techniques could quantify the sedimentation accumulation rate. As this area is prone to episodic sediment events (landslides) it is unlikely that the sedimentation rate will be consistent through time.

Historically, Reclamation designs their outlet structures to avoid burial within the first 100 years of operation. As the sedimentation rate is unknown, we cannot predict when the dead storage capacity will be lost, risking the utility of the outlet works.

9. Conclusions and Recommendations

9.1. Survey Methods and Data Analysis

The 2017 bathymetric survey, combined with 2010 LiDAR data for the above-water topography, has been used to produce a digital surface of the reservoir bottom. Datasets were combined in GIS. There was no overlapping data between the bathymetric survey and the LiDAR data. Linear interpolation between breaklines was applied to fill in the spatial data gap.

Reservoir surface areas were computed from this digital surface at 1-foot intervals to determine the 2017 storage capacity. Surface area and storage capacity were then interpolated at 0.01-foot intervals. The difference in reservoir surfaces over time can be attributed to sedimentation, but also the differences in survey methods. The latest surface area and storage capacity curves are comparable with the original curves. The use of modern survey methods (RTK-GPS, multibeam depth sounder, LiDAR) have produced a more accurate and precise digital surface of the reservoir bottom than past surveys using older methods (plane table, level, photogrammetry).

9.2. Sedimentation Progression and Location

Over the span of 37 years, sedimentation was not measurable given the differing survey techniques. As there are no repeat surveys, we cannot determine the sediment accumulation rate, sediment deposition spatial trends, or remaining useful life of the reservoir *(*see Section 8 Sedimentation Trends*)*. As Lake Creek is a cobble- and gravel- bed stream, we can assume that most sediment has deposited in the river delta. If any fine sediments are present, they would likely deposit in the Upper Lake. Any wash-load particles may deposit in the Lower Lake, risking the outlet works infrastructure, but the volume and risk is unknown.

9.3. Recommendation for Next Survey

Based on the unknown rates of sedimentation, the next survey of Twin Lakes Reservoir is recommended within 10 years, or by 2027. It is recommended to use the same survey technique documented in this report (multi-beam bathymetric survey combined with LiDAR data).

10. References

Bureau of Reclamation. (1985). *Surface Water Branch, ACAP85 User's Manual.* Denver, CO: Technical Service Center.

Bureau of Reclamation. (2005). *Standing Operating Proocedures for Twin Lakes Dam and Reservoir.* Technical Service Center. Denver, CO: Bureau of Reclamation.

Capps, S., & Leffingwell, E. (1904). Pleistocene Geology of the Sawatch Range Near Leadville, Colo. *The Journal of Geology, 12*(8), 698-706.

McCalpin, J., Funk, J., & Mendel, D. (2012). *Leadville South Quadrangle Geologic Map, Lake County, Colorado.* Denver, CO: Colorado Geological Survey.

Soil Survey Staff. (2017). *Web Soil Survey, United States Department of Agriculture. National Resource Conservation Service.* Retrieved from https://websoilsurvey.sc.egov.usda.gov/

U.S. Geological Survey. (2011). NLCD 2011 Land Cover - National Geospatial Data Asset Land Use Land Cover. Sioux Falls, South Dakota, U.S.A.

U.S. Geological Survey. (2014, 08 27). USGS Lidar Point Cloud (LPC) CO_ArkansasValley_2010_000012. LAS: U.S. Geological Survey.

U.S. Geological Survey. (2019). *StreamStats.* Retrieved from The StreamStats Program: http://streamstats.usgs.gov

Westgate, L. (1905). The Twin Lakes glaciated area, Colorado. *The Journal of Geology, 13*(4), 285-312.

Appendix A — Hydrographic Survey Equipment and Methods

The 2017 bathymetric survey was conducted from 6/19/2017 to 6/22/2017. During this period, daily reservoir water surface elevations varied from 9,195 to 9,197 feet (RPVD).

The survey was conducted along a series of cross section, longitudinal, and shore line survey lines (Figure 8). The survey lines were spaced approximately every 500 ft, close enough for adequate interpolation between multi-beam depth data.

The survey employed an 18-foot, flat-bottom aluminum Wooldridge boat powered by outboard jet and kicker motors (Figure 15). Reservoir depths were measured using multibeam echo sounder which consisted of the following equipment:

- variable-frequency transducer with integrated motion reference unit,
- near-surface sound velocity probe,
- two GPS receivers to monitor the boat position and heading,
- an external GPS radio, and
- processor box for synchronization of all depth, sound velocity, position, heading, and motion sensor data.

Figure 15. Wooldridge boat with RTK-GPS and multibeam depth sounder system.

The multibeam transducer emits up to 512 beams (user selectable) capable of projecting a swath width up to 120 degrees in 100 feet (30 meters) of water. Sound velocity profiles were collected over the full water depth at various locations throughout the reservoir. These sound velocity profiles measure the speed of sound through the water column, which can be affected by multiple characteristics such as water temperature and salinity. These sound velocity profiles were used to correct the depth measurements.

RTK GPS survey instruments were used to continuously monitor the survey boat position and measure other ground control points. The GPS base station and receiver was set up on a tripod over a point overlooking the reservoir (Figure 8). The coordinates of this point were computed using the Online Positioning User Service (OPUS) developed by the National Geodetic Survey (NGS) (www.ngs.noaa.gov/OPUS/). During the survey, position corrections were transmitted to the GPS rover receivers using an external GPS radio and UHF antenna (Figure 16). The base station was powered by a 12-volt battery.

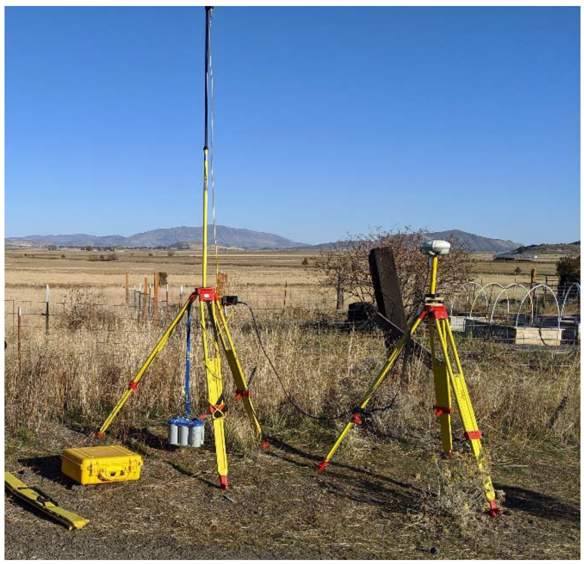


Figure 16. The RTK-GPS base station set-up used during the Klamath River Survey in Oregon is typical of the set up used for other bathymetric surveys.

The GPS rover receivers include an internal radio and external antenna mounted on a range pole (ground survey) or survey vessel (bathymetric survey). The rover GPS units receive the same satellite positioning data as the base station receiver, and at the same time. The rover units also receive real-time position correction information from the base station via radio transmission. This allows rover GPS units to measure accurate positions with precisions of ±2 cm horizontally and ±3 cm vertically for stationary points and within ±20 cm for the moving survey boat.

During the bathymetric survey, a laptop computer was connected to the GPS rover receivers and echo sounder system. Corrected positions from one GPS rover receiver and measured depths from the multibeam transducer were transmitted to the laptop computer through cable connections to the processor box. Using real-time GPS coordinates, the HYPACK software provided navigational guidance to the boat operator to steer along the predetermined survey lines.

The HYPACK hydrographic survey software was used to combine horizontal positions and depths to map the reservoir bathymetry in the user selected coordinate system, NAD 1983 State Plane, Colorado Central. Water surface elevations from dam gage records and RTK GPS measurements were used to convert the sonar depth measurements to reservoir-bottom elevations in the RPVD. The multibeam depth sounder generates millions of data points. Sometimes fish, underwater vegetation, or anomalies mean that a small portion of depth measurements do not represent the reservoir bottom and these data are deleted during the post processing. Final processing of the bathymetric data resulted in 2.5 million data points used in the development of the reservoir surface. Filtering of this large data file is necessary, so a raster is created in GIS (e.g. 1-foot square cells). For each raster cell, the reservoir bottom elevation is assigned equal to the median elevation of all available data points within that raster cell. The use of the median value reduces the influence of the highest and lowest elevations within the cell.

Appendix B – Above Water Survey Methods

Data from the 2010 LiDAR survey were used to represent the above-water reservoir topography, including the islands in the Upper Lake. These data were produced by the U.S. Geological Survey (USGS). Data were acquired in 2010 between September 9th and October 28th and published in 2014. The dataset is available through the National Map Viewer (https://viewer.nationalmap.gov/basic/).

The LiDAR data was flown seven years prior to the bathymetric survey. A comparison of aerial imagery within that timeframe suggests that the river delta and surrounding hillslopes have changed very little in between the two surveys (Figure 17).

The water surface elevation during the LiDAR flight was 9,190 (RPVD). During the 2017 bathymetric survey, the water surface elevation ranged from 9,195 to 9,197 feet (RPVD). No overlap data were collected as collecting data less than 5 ft of water depth put the multibeam system at an unnecessary risk. Furthermore, the multibeam system is less effective in shallow water depths (< 5 ft). Breaklines were digitized in both the bathymetric and LiDAR data. Linear interpolation was applied to fill the gap between datasets.

Figure 17. Comparison of aerial imagery of the river delta between 2011 and 2015 (most recent) at a similar water surface elevation.

Appendix C — Computation of Reservoir Surface Area, Storage Capacity, and Sedimentation Volume

A digital surface of the reservoir bottom was generated in GIS using the processed bathymetric data points (easting, northing, and elevation) combined with available above-water data. Horizontal surface areas were then computed at 1-foot increments, using functions within ArcGIS Pro, for the complete range of reservoir elevations (9,100 to 9,202 feet, RPVD). These reservoir surface areas were then used in Reclamation's Area-Capacity (ACAP) Program, 1985 Version (Reclamation, 1985), to compute the storage capacity at these increments and then interpolate surface areas and storage capacities at 0.01-foot increments between each 1-foot interval.

The program uses the least squares method to predict the reservoir storage capacity between 1-foot intervals using the following equation over a certain elevation interval:

$$V = A_1 + A_2(y - y_b) + A_3(y - y_b)^2$$

where: V = storage capacity (acre-feet)
y = reservoir elevation
y_b = reservoir elevation at bottom of elevation increment
A_1 = intercept and storage capacity at elevation y_b (acre-feet)
A_2 = surface area at elevation y_b (acres) and coefficient for linear rate of increase in storage capacity
A_3 = coefficient (feet) for nonlinear rate of increase in storage capacity

The reservoir surface area is computed from the derivative of the volume equation:

$$S = A_2 + 2A_3(y - y_b)$$

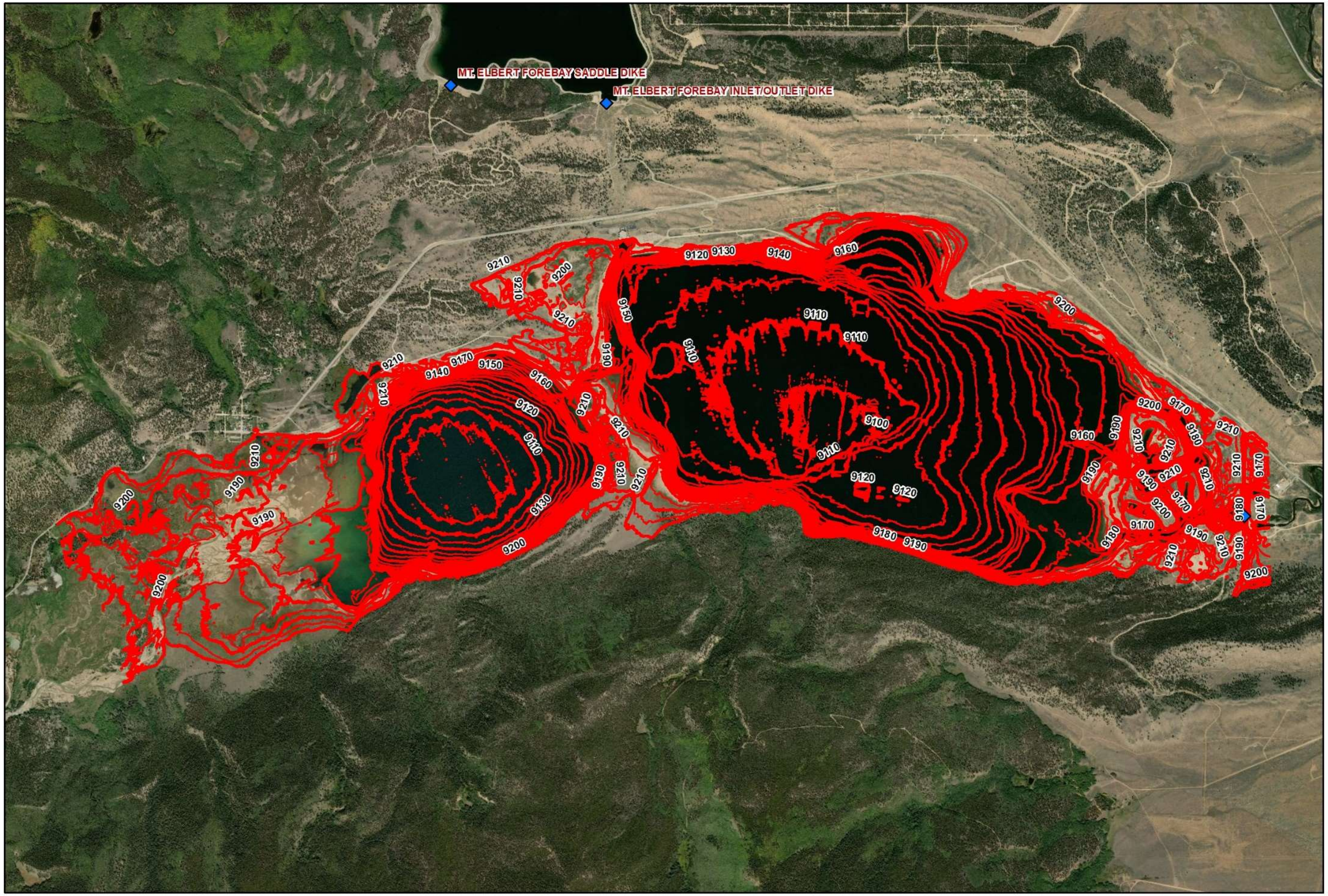
where: S = surface area (acres)

This method ensures that the given surface areas, and corresponding storage capacities, at the 1-foot intervals are not changed and there is a smooth transition in the interpolated values at the 0.01-foot intervals. The ACAP program produces the area and capacity tables for the full range of reservoir elevations. These data are documented in the report (Reclamation, 2005).

The sedimentation volume can be computed by subtracting digital surfaces of the predam reservoir surface from the 2017 digital reservoir surface. However, a predam topographic map and digital surface is not available for Twin Lakes Reservoir. A storage volume curve is available from the predam surface. It can be compared to the 2017 area capacity table to determine the change in reservoir storage. This method works well when the topographic map of the predam surface has good accuracy and precision. The accuracy and precision of the original storage capacity curve is unknown for Twin Lakes Reservoir. In this case, the original area and capacity tables underestimated the actual storage capacity and subsequent surveys show an increased storage capacity even though reservoir sedimentation has likely reduced the actual storage capacity.

Maps

Contour maps showing the results of the 2017 bathymetric survey are presented in the following figures.



Twin Lakes Reservoir Colorado Elevation Contour Map

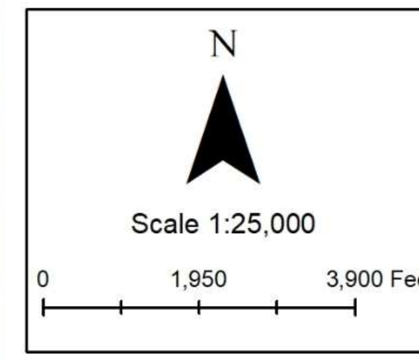
Overview Map

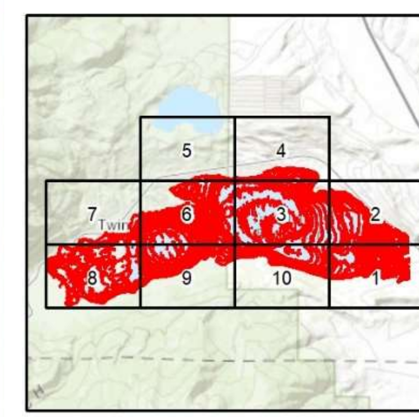
Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Twin Lakes Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.62 sft
NAVD88 – NGVD29 = 5.53 sft

Five Foot Contour Interval

Primary Data Source:
2017 Twin Lakes Study





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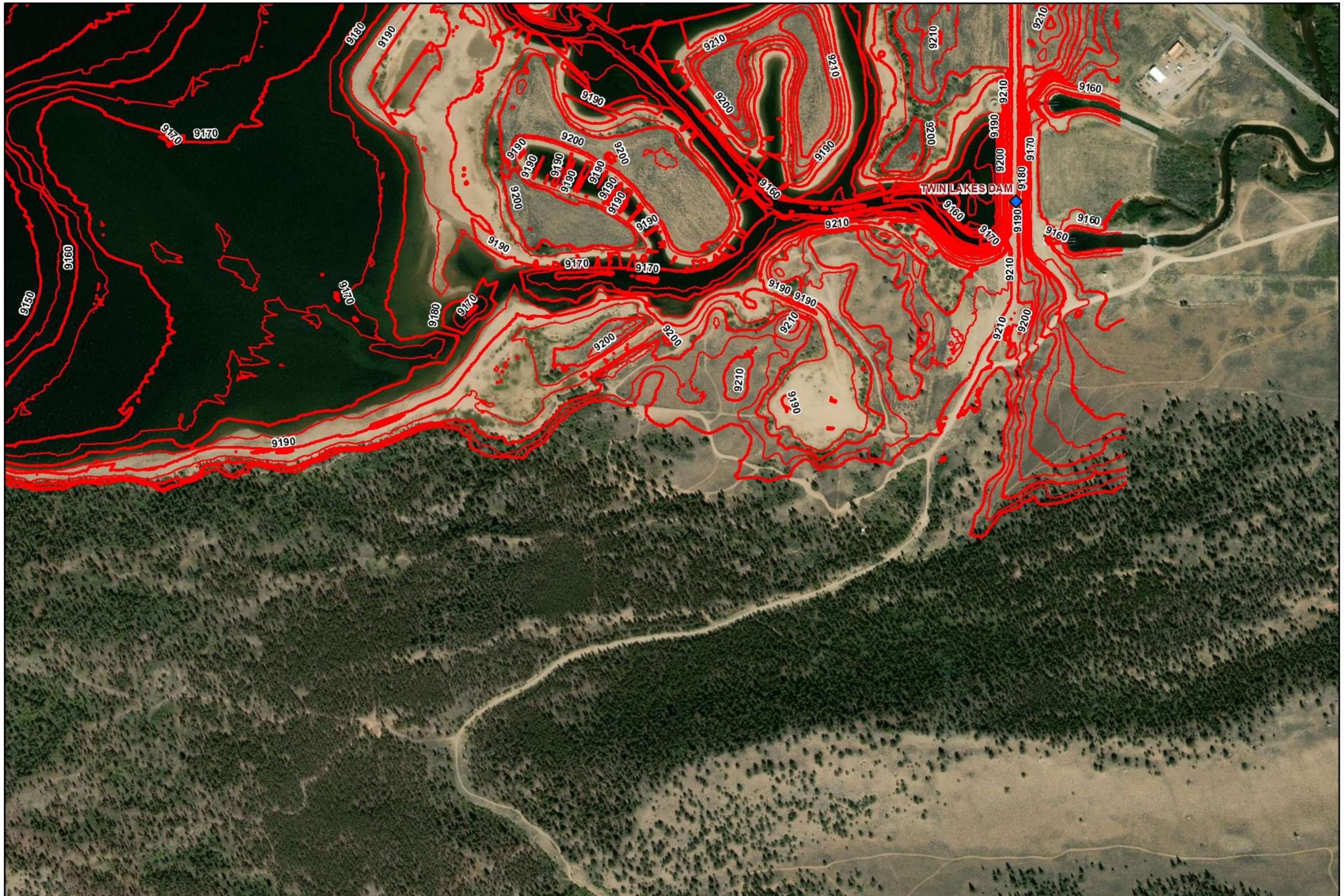


Twin Lakes Reservoir Colorado Elevation Contour Map

Sheet 1

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Twin Lakes Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 5.62 sft
NAVD88 – NGVD29 = 5.53 sft

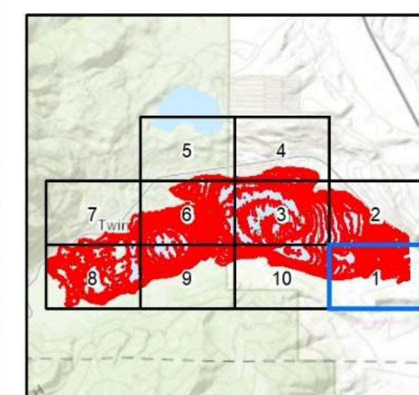
Five Foot Contour Interval

Primary Data Source:
2017 Twin Lakes Study

N

Scale 1:6,000

0 487.5 975 Feet



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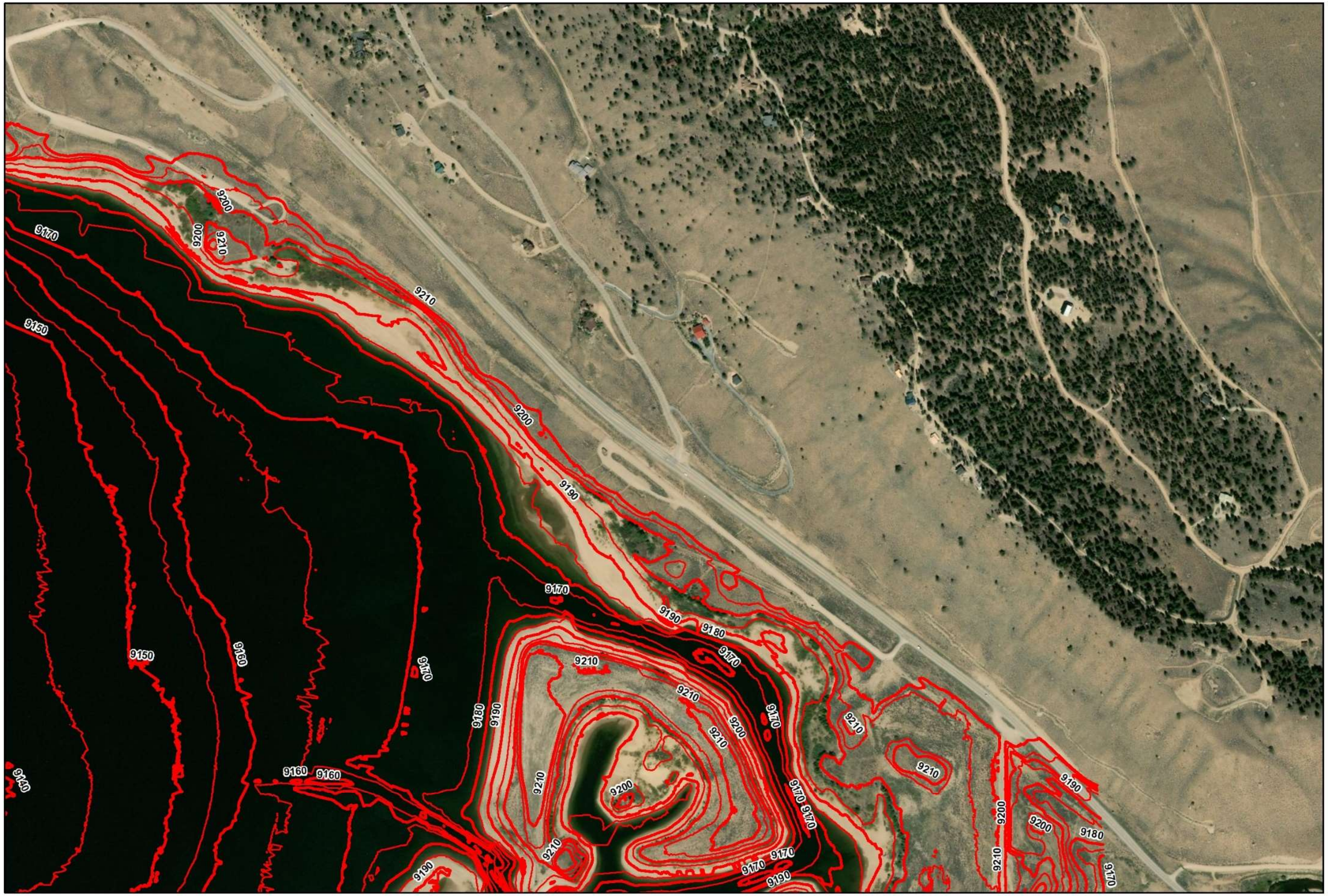


Twin Lakes Reservoir Colorado Elevation Contour Map

Sheet 2

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Twin Lakes Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.62 sft
NAVD88 – NGVD29 = 5.53 sft

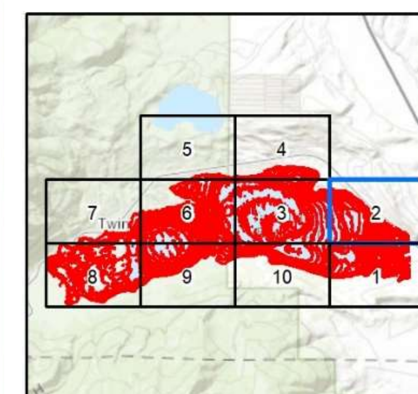
Five Foot Contour Interval

Primary Data Source:
2017 Twin Lakes Study

N

Scale 1:6,000

0 487.5 975 Feet



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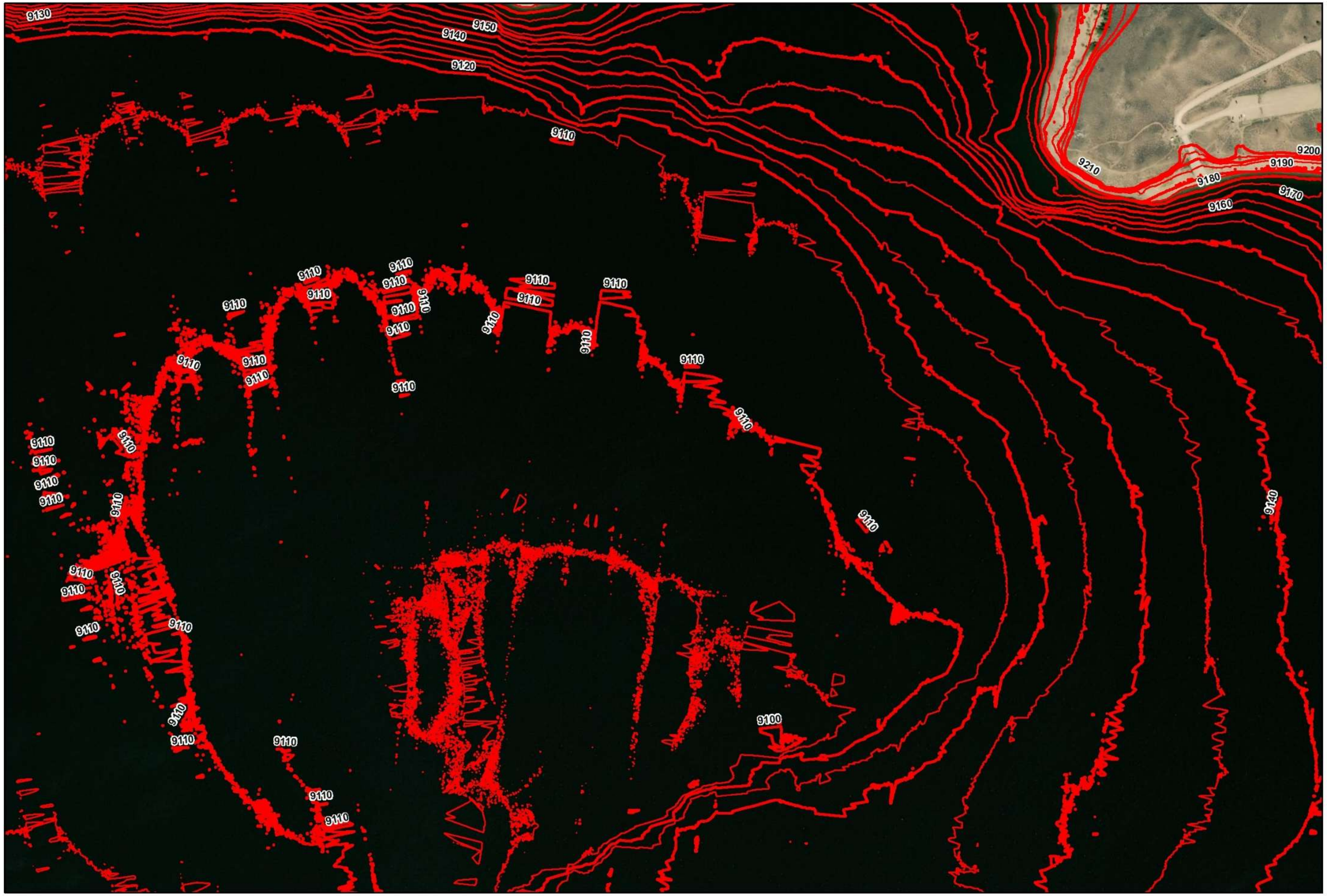


Twin Lakes Reservoir Colorado Elevation Contour Map

Sheet 3

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Twin Lakes Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 5.62 sft
NAVD88 – NGVD29 = 5.53 sft

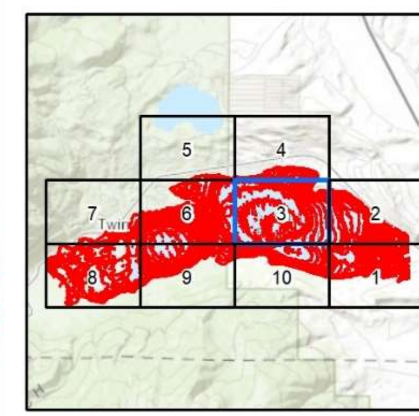
Five Foot Contour Interval

Primary Data Source:
2017 Twin Lakes Study

N

Scale 1:6,000

0 487.5 975 Feet



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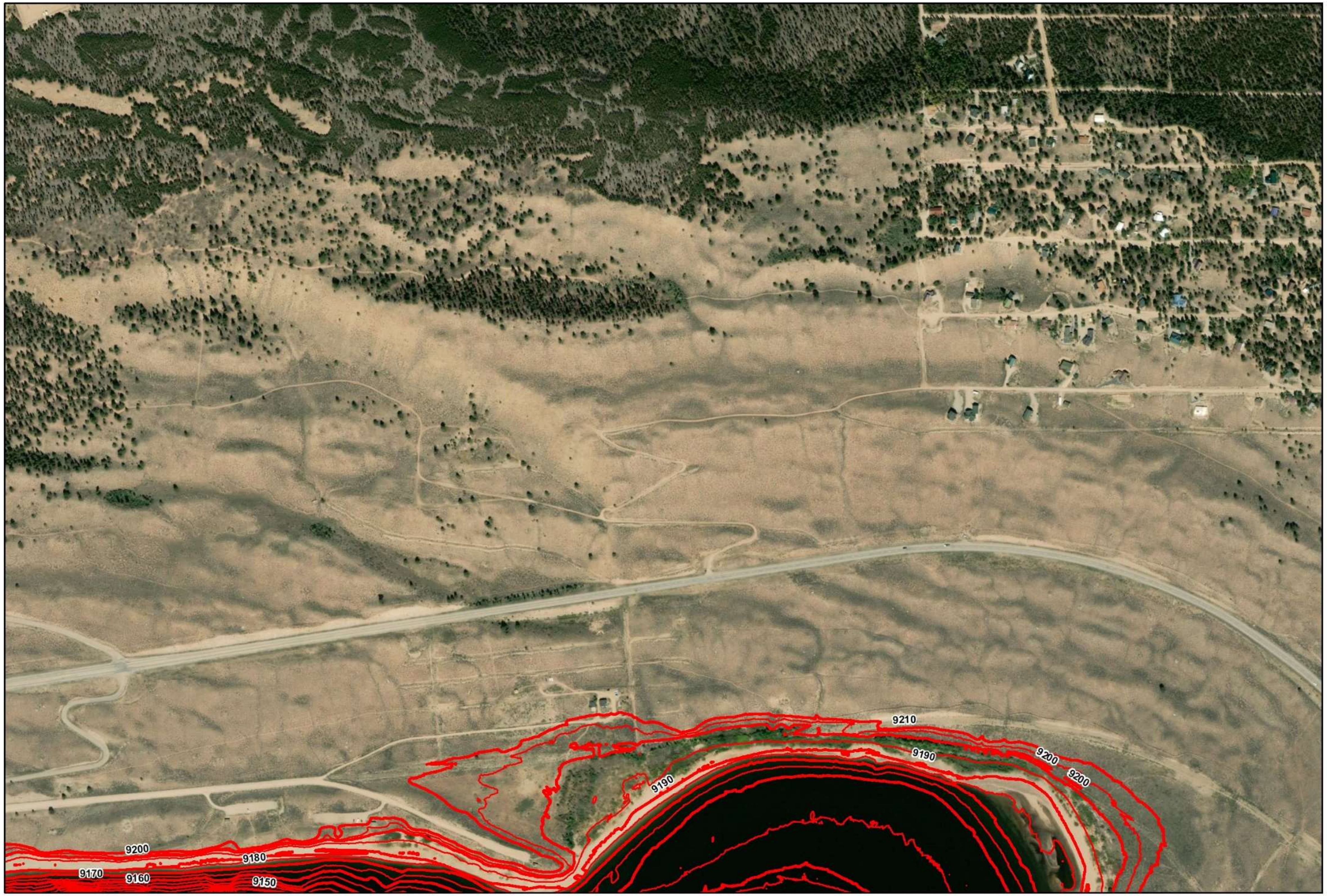


Twin Lakes Reservoir Colorado Elevation Contour Map

Sheet 4

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Twin Lakes Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.62 sft
NAVD88 – NGVD29 = 5.53 sft

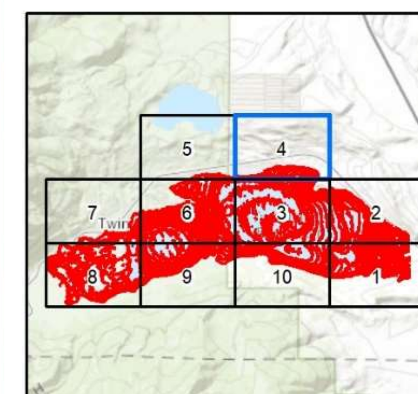
Five Foot Contour Interval

Primary Data Source:
2017 Twin Lakes Study

N

Scale 1:6,000

0 487.5 975 Feet



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Twin Lakes Reservoir Colorado Elevation Contour Map

Sheet 5

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Twin Lakes Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.62 sft
NAVD88 – NGVD29 = 5.53 sft

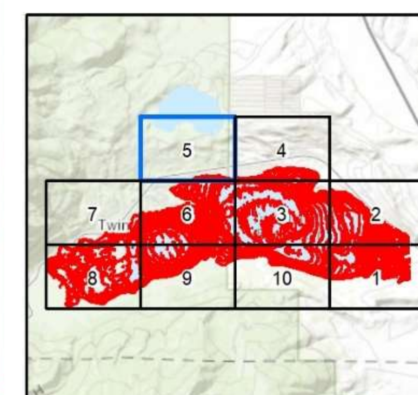
Five Foot Contour Interval

Primary Data Source:
2017 Twin Lakes Study

N

Scale 1:6,000

0 487.5 975 Feet



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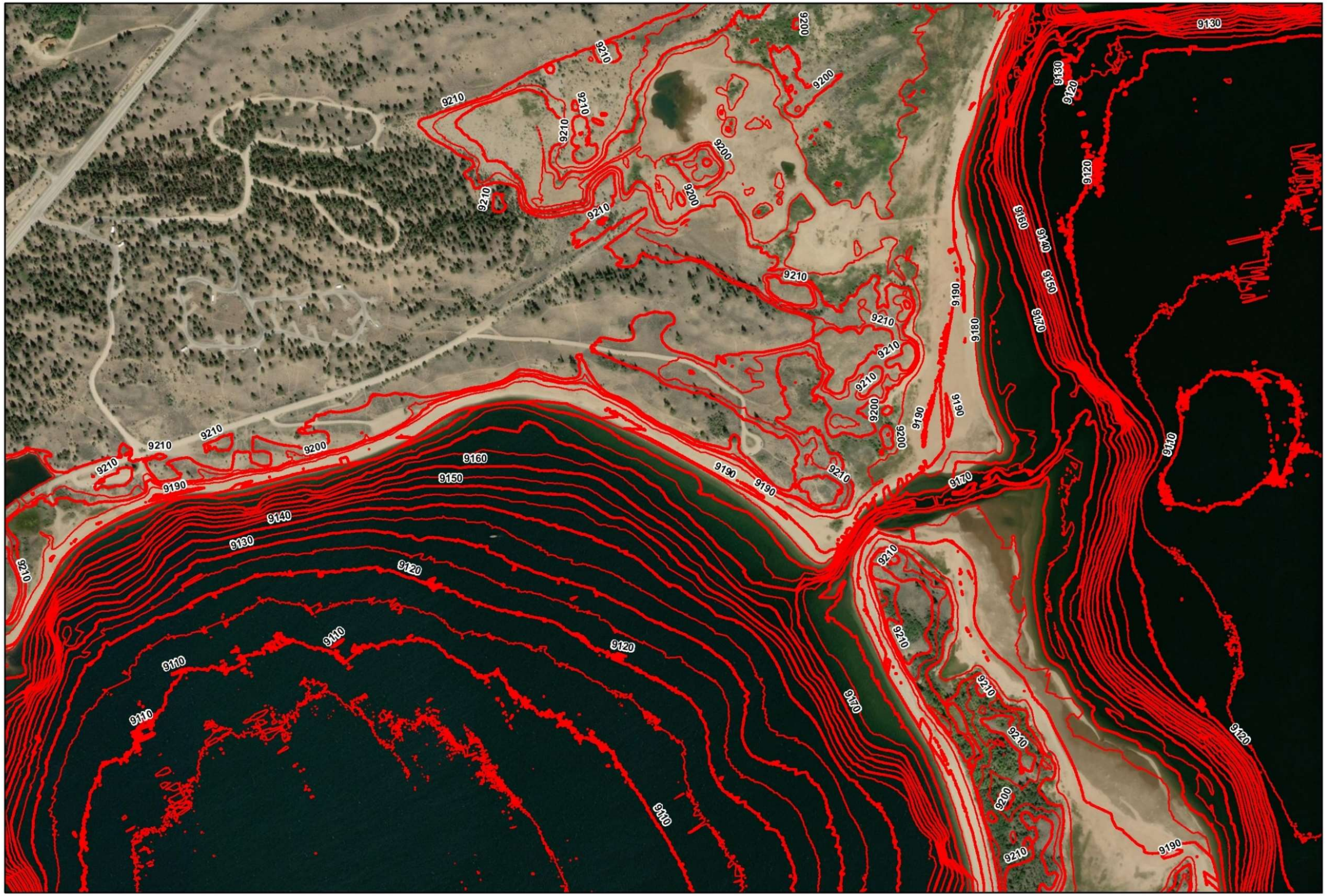


Twin Lakes Reservoir Colorado Elevation Contour Map

Sheet 6

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Twin Lakes Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 5.62 sft
NAVD88 – NGVD29 = 5.53 sft

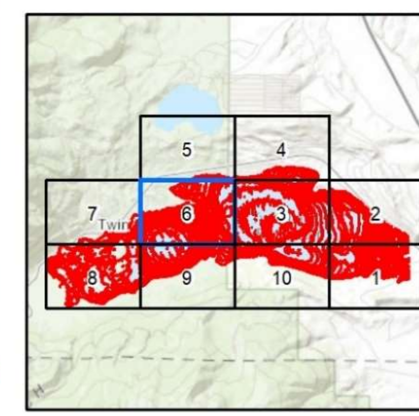
Five Foot Contour Interval

Primary Data Source:
2017 Twin Lakes Study

N

Scale 1:6,000

0 487.5 975 Feet



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Twin Lakes Reservoir
Colorado
Elevation
Contour Map

Sheet 7

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Twin Lakes Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.62 sft
NAVD88 – NGVD29 = 5.53 sft

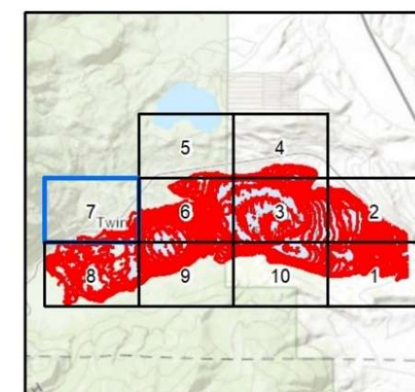
Five Foot Contour Interval

Primary Data Source:
2017 Twin Lakes Study

N

Scale 1:6,000

0 487.5 975 Feet



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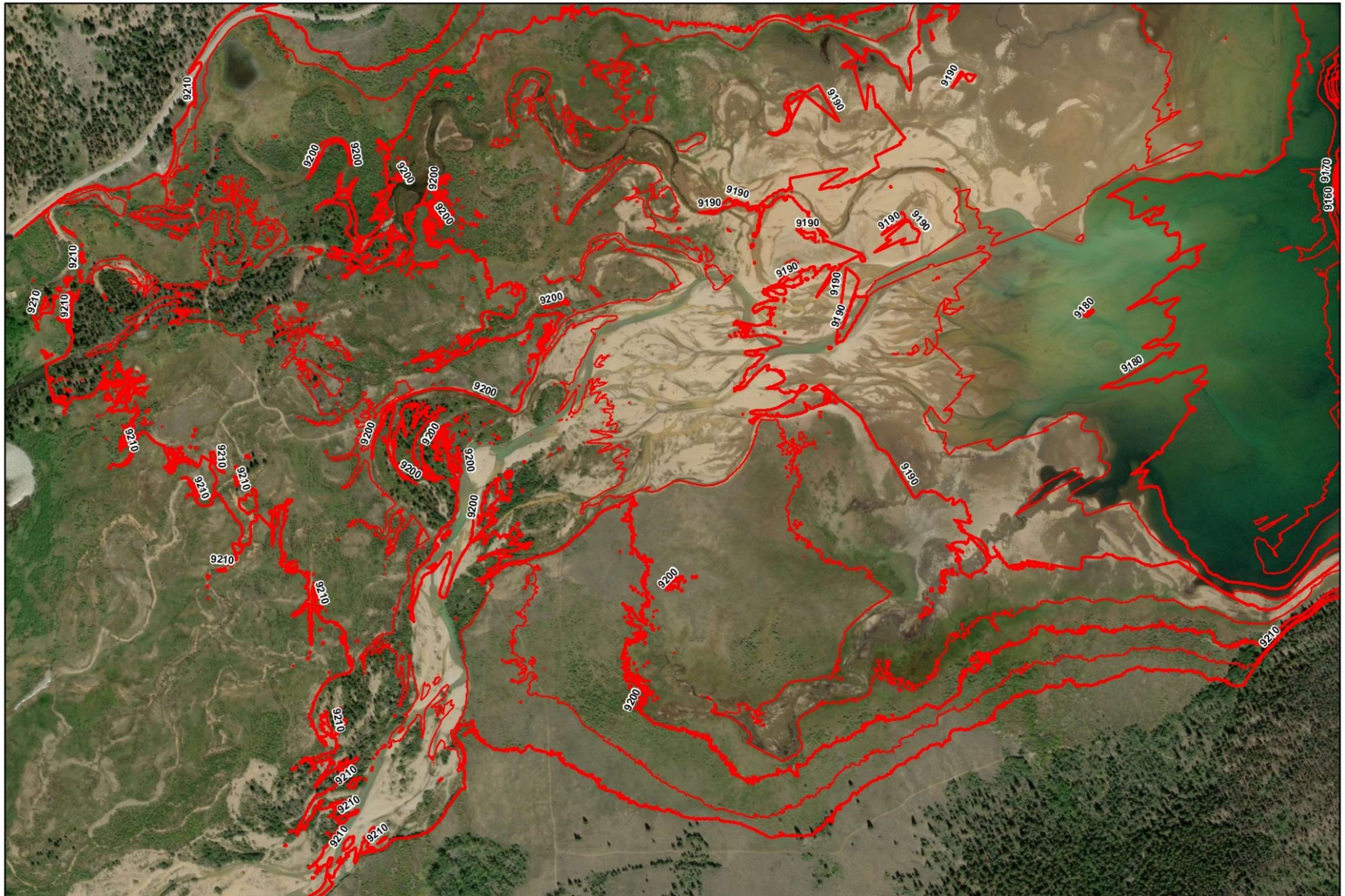


Twin Lakes Reservoir Colorado Elevation Contour Map

Sheet 8

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Twin Lakes Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 5.62 sft
NAVD88 – NGVD29 = 5.53 sft

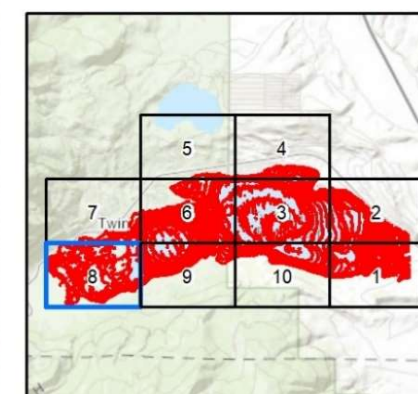
Five Foot Contour Interval

Primary Data Source:
2017 Twin Lakes Study

N

Scale 1:6,000

0 487.5 975 Feet



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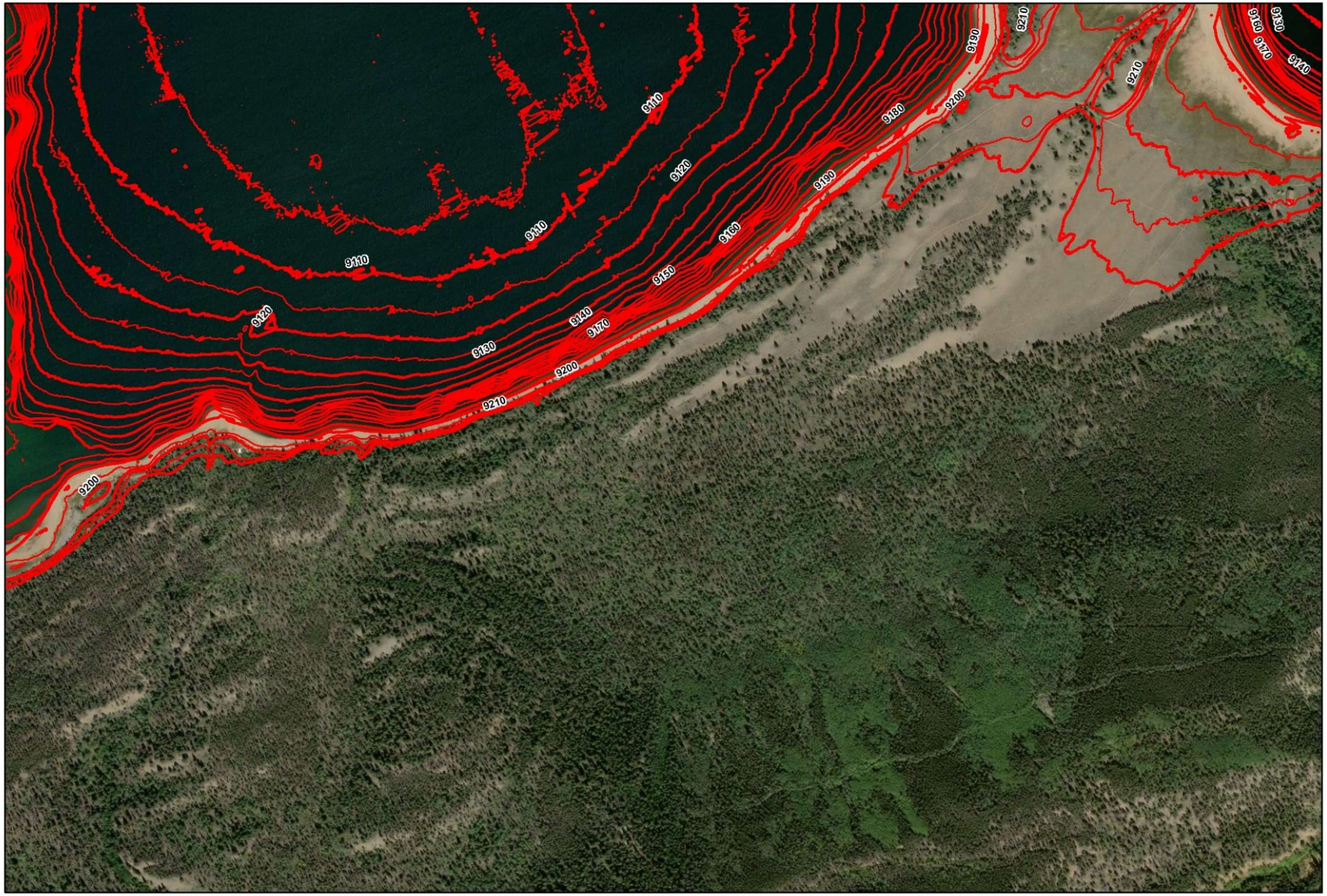


Twin Lakes Reservoir
Colorado
Elevation
Contour Map

Sheet 9

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface
Elevation Gage at Twin Lakes Dam
Referenced to Reclamation Project
Vertical Datum (RPVD)
NAVD88 – RPVD = 5.62 sft
NAVD88 – NGVD29 = 5.53 sft

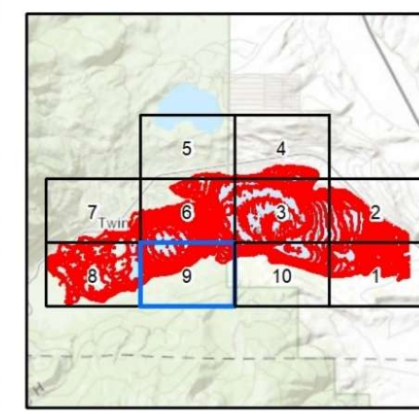
Five Foot Contour Interval

Primary Data Source:
2017 Twin Lakes Study

N

Scale 1:6,000

0 487.5 975 Feet



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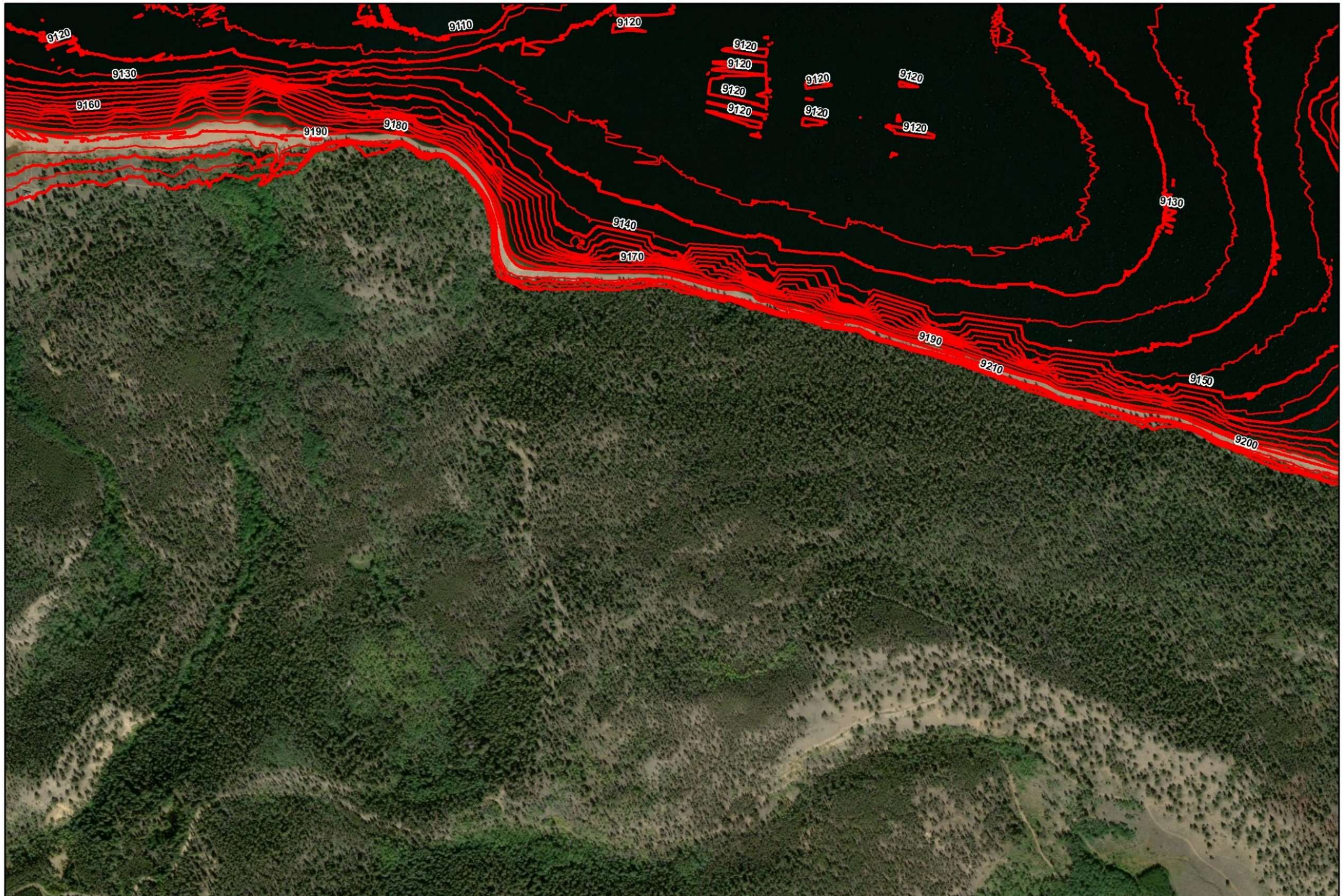


Twin Lakes Reservoir
Colorado
Elevation
Contour Map

Sheet 10

Horizontal Datum Based on NAD83 (2011)
State Plane Coordinates
Colorado Central Zone FIPS 0502
US Survey Feet

Vertical Datum Based on Water Surface Elevation Gage at Twin Lakes Dam Referenced to Reclamation Project Vertical Datum (RPVD)
NAVD88 – RPVD = 5.62 sft
NAVD88 – NGVD29 = 5.53 sft

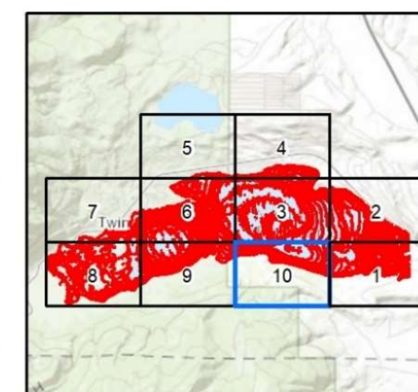
Five Foot Contour Interval

Primary Data Source:
2017 Twin Lakes Study

N

Scale 1:6,000

0 487.5 975 Feet



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